Food Science of Animal Resources

Food Sci. Anim. Resour. 2023 May 43(3):412~427
DOI https://doi.org/10.5851/kosfa.2023.e3

pISSN : 2636-0772 eISSN : 2636-0780
http://www.kosfaj.org

ARTICLE

Analysis of Quality after Sous Vide of Pork Loin Wet-Aged using Pulsed Electric Field System

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OPEN ACCESS

Received October 27, 2022
Revised December 30, 2022
Accepted January 6, 2023

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Abstract The effects of wet-aging using a commercial refrigerator (CR, 4°C) and a pulsed electric field refrigerator (PEFR, 0°C and –1°C) on the quality of sous vide pork loin were analyzed. The moisture and fat contents, pH, CIE L*, CIE b*, chroma, and shear force of the wet-aged samples were lower than those of the raw meat samples, whereas the water holding capacity (WHC) was higher. The PEFR group showed higher pH, CIE b*, chroma, and WHC and lower weight loss than the CR samples. Electronic nose analysis indicated that positive flavor compounds were induced whereas negative flavor compounds were inhibited in the PEFR group. Wet-aging increased the sourness, saltiness, and umami of sous vide pork loin; the PEFR 0°C samples showed the highest umami. Sensory evaluation indicated that wet-aging improved the color of sous vide pork loin. The PEFR 0°C samples were rated higher than the raw meat and CR samples for all sensory traits. In conclusion, sous vide after wet-aging using a PEFR improved the quality of pork loin.

Keywords pulsed electric field, wet-aging, sous vide, pork loin, quality

Introduction

Aging is a method applied to improve the tenderness and enhance the flavor of meat (Terjung et al., 2021). Wet-aging is an aging technique that involves vacuum packaging of meat and storing it in a refrigerated environment. It is widely used in the meat industry to enhance the flavor and taste of meat, as well as to extend its shelf life (Terjung et al., 2021). The tenderness of meat increases with the aging period because the activity of a proteolytic enzyme, calpain-1, and calpain-2, extends the degradation of muscle fibers (Kim et al., 2018). Hence, a long aging period is necessary to increase the tenderness of meat; however, such aging can also lead to risks of bacterial spoilage and quality deterioration (e.g., formation of undesirable flavors, reduced color stability and product yield; Kim et al., 2018). Therefore, a safe and superior-quality meat can be produced by developing an aging technique that can prolong the aging period by inhibiting the factors that cause spoilage and deterioration in quality.

Pulsed electric field (PEF) is a technology that suppresses the formation of ice crystals in supercooled food, i.e., food stored at a temperature lower than its freezing point. It minimizes deteriorations in the quality of food and keeps it fresh (Mok et al., 2015). PEF has been reported to enhance the tenderness of meat by increasing calpain activity and accelerating protein degradation; it also enables safe and hygienic long-term storage of meat by inactivating microbial growth (Gómez et al., 2019). These findings show that the PEF system can improve food quality and storage safety; it is expected to have synergistic effects when used in combination with other food processing systems.

“Sous vide” refers to the process of vacuum-packaging meat and cooking it in a water bath set at a precise temperature between 55℃ and 70℃ (Uttaro et al., 2019). Sous vide allows heat to be conducted evenly around the surface of food and prevents the loss of volatile flavor compounds and water content during cooking (Baldwin, 2012). Heating meat at a low temperature for a long period of time (e.g., ≥12–24 h) can enhance its tenderness (Baldwin, 2012). However, sous vide, which requires a long cooking time, is considered uneconomical considering the commercial costs involved. Hence, a method that can increase the commercial viability, e.g., by reducing the required cooking time, is required.

Pork is the second most consumed meat in the world, and it is known that there is a difference in intramuscular fat content depending on the retail cuts (Alfaia et al., 2019; Lee et al., 2016). In the case of intramuscular fat, the higher the content, the higher the sensory characteristics such as tenderness and taste of meat (Alfaia et al., 2019; Lee et al., 2016). Among them, pork loin has a relatively low intramuscular fat content compared to other retail cuts, and as a result, its sensory properties are inferior to other retail cuts (Lee et al., 2016). Therefore, there is a need for a processing method to be applied to improve the sensory characteristics of such pork loin.

Applying the wet-aging process prior to sous vide cooking can improve food quality by enhancing the tenderness via protein degradation and by generating high palatability and a flavor specific to the aging process. Moreover, aging complemented by a PEF system can be expected to further improve tenderness, taste, and flavor. Therefore, it is necessary to conduct additional research on sous vide cooking by applying a PEF system to the wet-aging process to produce high-quality meat. In this study, the effects of a PEF system on the physiochemical and sensory quality of wet-aged pork loin after sous vide were analyzed.

Materials and Methods

Wet-aging and sous vide of pork loins

Pig carcass left loin (*Longissimus thoracis et lumborum*) was obtained from Ihome Meat (Seoul, Korea) 24 h after slaughter. Wet-aging was performed in 3 batches, and 3 pork loin pieces were used in each batch according to different wet-aging conditions. The pork loin was divided into 3 parts with dimensions of 15×9×5 cm (length×width×height) and an average weight of 619.14±11.61 g (n=27). Each piece of pork loin was vacuum-packed with a vacuum packaging machine (C 15-HL, Webomatic, Bochum, Germany). The vacuum-packed samples were aged in a commercial refrigerator (CR; CA-H17DZ, LG, Seoul, Korea) and a PEF refrigerator (PEFR; ARD-090RM-F, Mars, Fukushima, Japan) under the following conditions: CR, temperature 4±1℃, wind speed 5±3 m/s; and PEFR, temperature 0±0.1℃ or –1±0.1℃, wind speed 5±2 m/s, voltage 7 kV. For the setting of the aging period, the week that received the highest evaluation as a result of sensory evaluation in the previous study was set, and the later weeks were excluded because they were sensory deteriorated. The aging period was set as 2 weeks for CR, 3 weeks for PEFR 0℃, and 4 weeks for PEFR –1℃, compliant with storage stability as reported in a previous study (Table 1).

Table 1. Thiobarbituric acid reactive substances (TBARS), volatile basic nitrogen (VBN), and total plate count (TPC) of the sous vide pork loin and sous vide after wet-aging with different conditions

Traits	Raw meat	Wet-aging conditions			SEM
		CR (2 wk)	PEFR		
			0°C (3 wk)	−1°C (4 wk)	
TBARS (mg MDA/kg)	0.20±0.01[c]	0.22±0.01[a]	0.21±0.01[a]	0.21±0.01[b]	0.002
VBN (mg/100 g)	1.87±0.32[c]	3.74±0.32[a]	3.17±0.28[b]	2.99±0.32[b]	0.159
TPC (Log CFU/g)	1.99±0.20[d]	5.67±0.30[a]	3.25±0.40[c]	3.74±0.16[b]	0.405

All values are expressed as mean±SE.
[a–d] Means in the same row with different letters are significantly different ($p<0.05$).
CR, commercial refrigerator; PEFR, pulsed electric field refrigerator; MDA, malondialdehyde.

Sous vide of wet-aged pork loin was performed in three independent batches, and the samples were classified as follows according to the wet-aging conditions: Raw meat (no wet-aging), CR (CR 4°C, wet-aged for 2 weeks), PEFR 0°C (PEFR 0°C, wet-aged for 3 weeks), and PEFR –1°C (PEFR –1°C, wet-aged for 4 weeks). Each sample of pork loin was prepared and cut into dimensions of 2×9×5 cm (length×width×height) with an average weight of 81.99±2.33 g (n=36) and vacuum-packed in a vacuum packaging machine (C 15-HL, Webomatic). Sous vide of pork loin was carried out using the method described by Kurp et al. (2022). The vacuum-packed pork loin samples were cooked in a water bath (JSWB-30T, JSR, Gongju, Korea) set at 65°C for 2 h, i.e., until the core temperature reached 65°C. After the sous vide, the pork loin samples were immediately immersed in iced water and cooled for 20 min. The samples were then stored at 4°C until the experiment was performed.

Proximate compositions

The proximate compositions of the samples were measured and calculated by converting the moisture content (AOAC-925.10), protein content (AOAC-960.52), fat content (AOAC-2003.05), and ash content (AOAC-923.03) according to Horowitz and Latimer (2005).

pH

The samples were homogenized at 1 min, 6,451×g using ultra-turrax (HMZ-20DN, Poonglim Tech, Seongnam, Korea) by mixing 4 g of sample with 16 mL of distilled water after cooking. The homogenate was then measured with a glass electrode pH meter (Model S220, Mettler-Toledo, Schwerzenbach, Switzerland). The glass electrode pH meter was calibrated using pH 4.01, pH 7.00, and pH 10.00 buffer solutions at 22°C (Suntex Instruments, New Taipei City, Taiwan).

CIE color, chroma, and hue angle

The sample was cut after cooking and bloomed by exposing it to air at room temperature for 30 minutes to determine its color. Thereafter, CIE L*, CIE a*, and CIE b* were measured using a colorimeter with attached the CR-A92 aperture (CR-10, Konica Minolta, Tokyo, Japan; standard illuminant D65, wide-angle 10°) on the cut surface. The standard color at that time was a white standard plate of CIE L* +97.83, CIE a* –0.43, and CIE b* +1.98. Chroma value was calculated as Chroma = $[(a^*)^2 + (b^*)^2]^{1/2}$. Hue angle was calculated as hue angle = arctan (b*/a*) × (180/π) at 360°, 0 (=360) = +a*, 90 = +b*, 180 = –a* and 270 = –b*.

Water holding capacity (WHC)

The WHC before cooking was measured according to the method of Ortuño et al. (2015). The inner central part of the sample was cut into 0.3 g and pressed on a filter-paper press device for 3 minutes. Afterward, it was calculated by measuring the total and inner area (sample area).

$$\text{WHC (\%)} = \frac{\text{Inner area (mm}^2\text{)}}{\text{Total area (mm}^2\text{)}} \times 100 \quad (1)$$

Weight loss

The weight loss was divided into aging loss, cooking loss, and total loss, and each measurement was performed as follows. Aging loss was calculated using the weight before and after wet-aging of each sample. The weight was measured after removing the surface moisture from the pork loin. For measuring the cooking yield of the sample, sous vide was performed as described above, and the weight was measured before and after sous vide cooking after removing the surface moisture. The total loss was calculated by adding the aging loss and the cooking loss.

$$\text{Aging loss (\%)} = \frac{\text{Weight before aging (g)} - \text{Weight after aging (g)}}{\text{Weight before aging (g)}} \times 100 \quad (2)$$

$$\text{Cooking loss (\%)} = \frac{\text{Weight before cooking (g)} - \text{Weight after cooking (g)}}{\text{Weight before cooking (g)}} \times 100 \quad (3)$$

Shear force

The shear force of samples was used after cooking samples. After cooking samples were measured three times by cutting each cooked samples into 2×1×1 cm (length×width×height), and a texture analyzer (TA 1, Lloyd, Largo, FL, USA) equipped with a v-blade under the following conditions was used: Head speed 2.0 mm/s, distance 2.0 mm, force 5 g. The sample was placed so that the direction of the myofibril was perpendicular to the v-blade, and the measurement result was denoted as N.

Electronic nose

Electronic nose analysis was performed according to the method of Park and Kim (2022). For analysis, 5 g of each cooked sample was placed in a 20 mL head-space vial and sealed. Thereafter, the analysis was performed using flash gas chromatography electronic nose (Heracles NEO, Alpha MOS, Toulouse, France) under the following conditions: Gas chromatography injection port, injection rate 125 μL, injection temperature 200℃, trap absorption temperature 80℃, trap desorption temperature 250℃, acquisition time 110s, MXT-5 column, and MXT-1701 column. The measured flavor compounds were identified based on the Kovats index.

Electronic tongue

Electronic tongue analysis was performed using a taste sensor e-tongue (Astree V, Alpha MOS). Each sous vide pork loin sample (8 g) was homogenized for 1 min at 6,451×g using 32 mL of distilled water and a homogenizer (AM-5, Nissei, Tokyo, Japan). The homogenized sample was filtered with filter paper (Whatman No. 1, GE Healthcare, Chicago, IL, USA) and the supernatant was collected. The supernatant was diluted 1,000-fold in distilled water and measured using the taste sensor e-tongue. The analysis measured the signal intensity at each sensor using taste sensors: CTS (saltiness), NMS (umami), and AHS (sourness), along with auxiliary sensors SCS and CPS, and standard sensors PKS and ANS.

Sensory evaluation

Eighteen sensory panelists used a basic taste identification test to evaluate the sensory characteristics of the sous vide pork loin and wet-aged pork loin samples. Panelists consisted of undergraduate and graduate students, majoring in food science related fields, who were trained using commercially available sous vide pork loin and wet-aged pork loin products for seven days (1 h session per day); to ensure familiarization with the sensory characteristics, of sous vide pork loin and wet-aged pork loin samples, to be evaluated. The sensory evaluation session for sous vide pork loin for each treatment groups were performed for each period of wet-aging, and three sessions were conducted per batch to complete the evaluation (a total of 9 sessions) of all treatment groups. The sensory evaluation samples were roasted at 80°C, cut into 2×1×1 cm pieces, and then cooled down for 3 minutes before serving. Sensory evaluation panelists were provided with three sensory samples for each sample; and each sample was served randomly, with a time of 3 minutes between evaluation intervals. Each sensory characteristic item was evaluated on a scale of 10 points; 10=extremely good or desirable, 1=extremely bad or undesirable. Sensory evaluation of this study was approved by the Ethics Committee of Kongju National University, Korea (Authority No: KNU_IRB_2022-083).

Statistical analysis

The experiments in this study were designed in four independent batches (12 carcass×3 times). For each batch, sous vide pork loin (raw meat; CR, 4°C; PEFR, 0°C and –1°C) under four different wet-aging conditions were analyzed. In all experiments except sensory evaluation, wet-aging conditions were considered a fixed effect, and the batches were considered a random effect. For sensory evaluation, wet-aging conditions and panelists considered a fixed effect, and the batches and sessions were considered a random effect. All collected data were subjected to analysis of variance (ANOVA) for all variances and statistically analyzed using Duncan's multiple range test ($p<0.05$) and the general linear model of SAS (version 9.4 for window, SAS Institute, Cary, NC, USA), a statistical processing program. Results were expressed as mean, SE, and SEM. Electronic nose was analyzed using Alphasoft 14.2 (Alpha MOS). The measured data of the e-nose determined the difference between samples through principal component analysis (PCA) and volatile compounds graphs. Electronic tongue data were interpreted using a radar chart.

Results and Discussion

Proximate compositions and pH

Table 2 shows the results of proximate composition measurements for wet-aged pork loin samples. The moisture level was significantly higher in the PEFR group than in the raw meat samples ($p<0.05$). Aging of meat causes protein degradation and breaks down the myofibril structure, which allows more water molecules to be trapped and increases the WHC (Farouk et al., 2012). A similar finding was reported by Watanabe et al. (2018), showing a negative correlation between water and fat contents in pork and beef. Hence, it can be assumed that the water content of the pork loin wet-aged using the PEFR increased due to an increase in the WHC. The protein level was significantly higher in the CR samples than in the PEFR –1°C

Table 2. Proximate compositions and pH of the sous vide pork loin and sous vide after wet-aging with different conditions

Traits	Raw meat	Wet-aging conditions			SEM
		CR (2 wk)	PEFR		
			0°C (3 wk)	–1°C (4 wk)	
Moisture (%)	62.22±2.01[b]	64.11±2.04[ab]	65.27±0.70[a]	66.96±0.97[a]	0.646
Protein (%)	32.58±0.34[ab]	33.03±0.90[a]	32.14±0.21[ab]	31.42±0.31[b]	0.263
Fat (%)	5.59±0.27[a]	2.61±0.35[b]	3.01±0.03[b]	3.13±0.40[b]	0.416
Ash (%)	1.59±0.29	1.75±0.20	1.51±0.03	1.34±0.15	0.077
pH	6.02±0.01[a]	5.68±0.01[d]	5.70±0.01[c]	5.72±0.01[b]	0.041

All values are expressed as mean±SE.
[a–d] Means in the same row with different letters are significantly different (p<0.05).
CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

samples (p<0.05), and the fat content was significantly lower in the wet-aged group than in the raw meat samples (p<0.05). Aging causes degradation of sarcoplasmic proteins in meat, and the degraded proteins are excreted together with water molecules during the cooking process (Macharáčková et al., 2021). Therefore, it can be assumed that the low protein content found in the PEFR –1°C samples was due to the relatively long aging period and additional protein degradation. In addition, it has been reported that loss of water leads to a corresponding increase in the levels of protein and fat (Kim et al., 2019a), consistent with the findings of this study. There were no significant differences in the ash content between all the sous vide pork loin samples (p>0.05), indicating that wet-aging does not affect the ash content of pork loin after sous vide. In summary, it appears that the application of PEF affected on the water, protein, and fat contents of wet-aged pork loin after sous vide.

Table 2 shows the results of pH measurements for wet-aged pork loin after sous vide. The pH was significantly lower in the wet-aged group than in the raw meat samples (p<0.05) and significantly increased with a decrease in the wet-aging temperature (p<0.05). Sous vide meat generally goes through a second stage of heating, and the Maillard reaction caused by this heat application is known to maximize the flavor of the meat (Baldwin, 2012). The Maillard reaction is enhanced by higher pH and an increase in the level of reactive substances, unprotonated amino groups, and open-chain reducing sugars, leading to an improvement taste and flavor (Rannou et al., 2016). Using the PEFR system allows long-term wet-aging without quality deterioration and increases the pH of sous vide pork loin. Therefore, although the pH of the PEFR sample was lower than that of the raw meat samples, it is considered that the flavor can be improved by enhancing the Maillard reaction compared to CR. In addition, wet-aging of pork loin takes place in an anaerobic environment, which is favorable for the growth of lactic acid bacteria. Hence, the low pH value in the wet-aged group could have been due to the accumulation of lactic acid (Kim et al., 2017). The increase in pH during aging could have been due to the products of protein degradation caused by endogenous proteolytic enzymes and the proliferation of microorganisms. Therefore, it can be assumed that as the aging period increased, the pH also increased (Rodríguez-Calleja et al., 2005; Wyrwisz et al., 2016). In summary, wet-aging leads to a decrease in the pH of sous vide pork loin, whereas extending the period of wet-aging can lead to an increase in the pH level.

CIE color, chroma, and hue angle

Table 3 shows the results of color measurements after sous vide of wet-aged pork loin. CIE L* was significantly lower in the wet-aged group than in the raw meat samples (p<0.05) and higher in the PEFR –1°C samples than in the CR and PEFR

Table 3. CIE color, chroma, and hue angle of the sous vide pork loin and sous vide after wet-aging with different conditions

Traits		Raw meat	Wet-aging conditions			SEM
			CR (2 wk)	PEFR		
				0°C (3 wk)	–1°C (4 wk)	
Color	CIE L*	77.00±0.30[a]	74.40±0.26[c]	74.50±0.36[c]	75.87±0.85[b]	0.346
	CIE a*	4.23±0.29	3.93±0.12	4.13±0.31	4.37±0.45	0.091
	CIE b*	17.03±0.21[a]	14.63±0.06[c]	15.80±0.71[b]	15.33±0.21[b]	0.299
	Chroma	17.55±0.27[a]	15.15±0.03[c]	16.30±0.75[b]	15.95±0.20[b]	0.298
	Hue angle	76.05±0.76	74.95±0.48	75.50±0.58	74.11±1.62	0.323

All values are expressed as mean±SE.
[a–c] Means in the same row with different letters are significantly different (p<0.05).
CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

0°C samples (p<0.05). Ángel-Rendón et al. (2020) reported that sous vide pork generally has a more pale appearance than roasted pork; this difference is associated with a high CIE L* and leads to a decrease in the visual preference of consumers. Since wet-aging of pork reduces the CIE L*, it can improve the color perceptions of consumers for sous vide meat. There were no significant differences in CIE a* among the pork loin samples (p>0.05); however, the CIE b* was significantly higher in the raw meat samples than in the other samples (p<0.05) and higher in the PEFR group than in the CR group (p<0.05). During aging, sarcoplasmic proteins effuse from the muscle of meat, leading to a decrease in the myoglobin concentration after sous vide of wet-aged pork loin. Furthermore, since this process suppresses the formation of metmyoglobin, which is responsible for an increase in CIE b*, the CIE b* appears to decrease after aging (Roldán et al., 2013; Yu et al., 2021). The CIE b* in the PEFR group (0°C and –1°C) after 3 weeks of aging was higher than that after 2 weeks of aging, showing that an increase in the aging period increases the CIE b* of sous vide pork loin. Wang et al. (2022) reported that as the aging period increases, oxidation of muscle also increases, leading to more CIE b*. Chroma was significantly higher in the raw meat samples than in the wet-aged group (p<0.05) and higher in the PEFR group than in the CR samples (p<0.05). Such changes in chroma can be attributed to the changes in CIE b*. An increase in chroma signifies that the color of the meat is more vivid, and chroma has been reported to increase with myoglobin concentration and a decrease in the denaturation level (Aroeira et al., 2017; del Pulgar et al., 2012). The decrease in chroma could also have been caused by a decrease in myoglobin concentration due to effusion of myofibril proteins during wet-aging (Yu et al., 2021). However, the PEFR group showed a higher level of chroma than the CR samples, indicating that the application of PEF may be effective in preventing a decrease in chroma after sous vide of wet-aged pork loin. There was no significant difference in the hue angle among the pork loin samples (p>0.05). A high hue angle of meat signifies low color stability; therefore, the findings of this study indicate that wet-aging does not affect the color stability of sous vide pork loin (Aroeira et al., 2017). All the color measurements described hereinabove indicate that wet-aging before sous vide of pork loin can improve the color perception of the consumers.

Water holding capacity (WHC) and shear force

Fig. 1 shows the results of WHC measurements after sous vide of wet-aged pork loin. WHC before heating was significantly higher for the PEFR group than for the raw meat and CR samples (p<0.05), and highest for the PEFR –1°C samples (p<0.05). WHC after heating was significantly higher for the raw meat and PEFR samples than for the CR samples

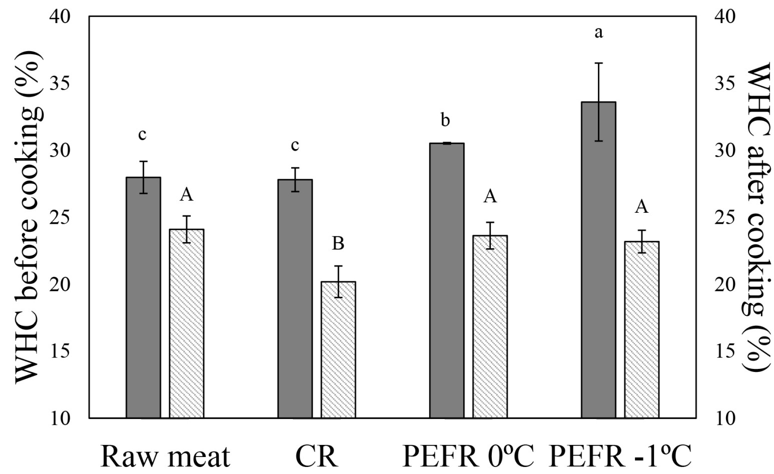


Fig. 1. Water holding capacity (WHC) of the sous vide pork loin and sous vide after wet-aging with different conditions. [A,B, a–c] Mean on the same bars with different letters are significantly different ($p<0.05$). CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

($p<0.05$). Aging causes degradation of myofibrils in meat and alters the structures associated with water loss. These alterations prevent water loss and lead to an increase in the WHC. Higher pH has a positive effect on such increases in the WHC (Farouk et al., 2012). Hence, it appears that the higher pH in the PEFR group than in the CR samples contributed positively to the increase in the WHC of the former. Hence, it can be assumed that using a PEFR to wet-age pork loin at low temperatures can enhance WHC during sous vide cooking.

Fig. 2 shows the results of shear force measurements after sous vide of wet-aged pork loin. Shear force was significantly lower for the wet-aged group than for the raw meat sample ($p<0.05$). Aging causes degradation of myofibril proteins, leading to fragmentation of myofibrils, which enhances tenderness (Kołczak et al., 2003). Similarly, Kim et al. (2019b) reported that wet-aging of beef led to a decrease in shear force due to the degradation of myofibril and cytoskeletal proteins by proteolytic enzymes. Li et al. (2019) reported that after sous vide, pork wet-aged for 10 days showed lower shear force than that aged for 1 day. These results indicate that wet-aging reduces the shear force of pork loin, and that sous vide can further reduce it.

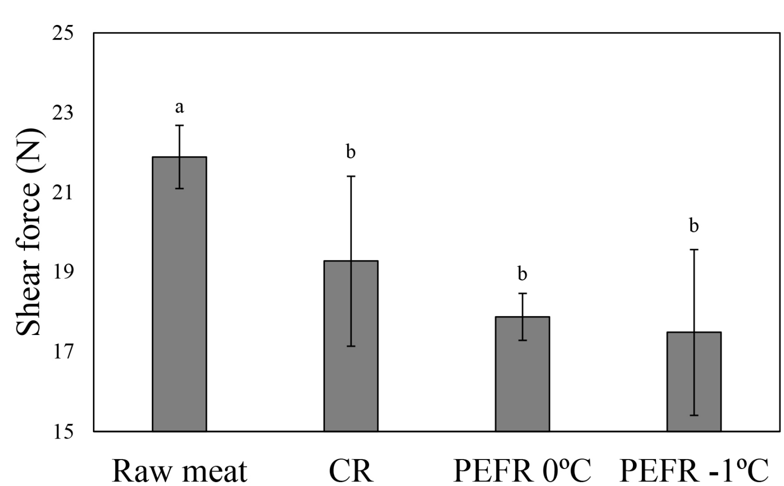


Fig. 2. Shear force of the sous vide pork loin and sous vide after wet-aging with different conditions. [a,b] Mean on the same bars with different letters are significantly different ($p<0.05$). CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

Weight loss

Table 4 shows the results of weight loss measurements after sous vide of wet-aged pork loin. Aging loss was significantly higher in the CR samples than in the PEFR group (p<0.05). Cooking loss was significantly higher in the CR samples than in the raw meat sample (p<0.05). In terms of total loss, the CR sample was significantly highest, and the raw meat sample was significantly lowest (p<0.05). Such weight loss is directly affected by the differences in the WHC of the samples. The difference in weight loss can also be attributed to an increase in effusion through "drip channels" during aging because the viscosity of the exudate increases with temperature and a decrease in pH (Rodrigues et al., 2022). Hence, wet-aging at a low temperature using a PEFR can reduce aging loss. Moreover, applying heat to meat decreases the WHC and induces the contraction of myofibrils, causing water loss in the muscle (Bıyıklı et al., 2020; Naqvi et al., 2021). Therefore, the differences in cooking loss after sous vide of wet-aged pork loin samples can be assumed to be due to a lower post-heating WHC of the CR samples compared with that of the PEFR group. This indicates that sous vide of wet-aged pork loin using a PEFR may reduce cooking loss. Moreover, total loss, which is a combination of aging loss and cooking loss, appears to have been affected by the overall temperature and pH depending on the aging period and WHC. In summary, applying PEF before sous vide of wet-aged pork loin can improve weight loss compared to CR.

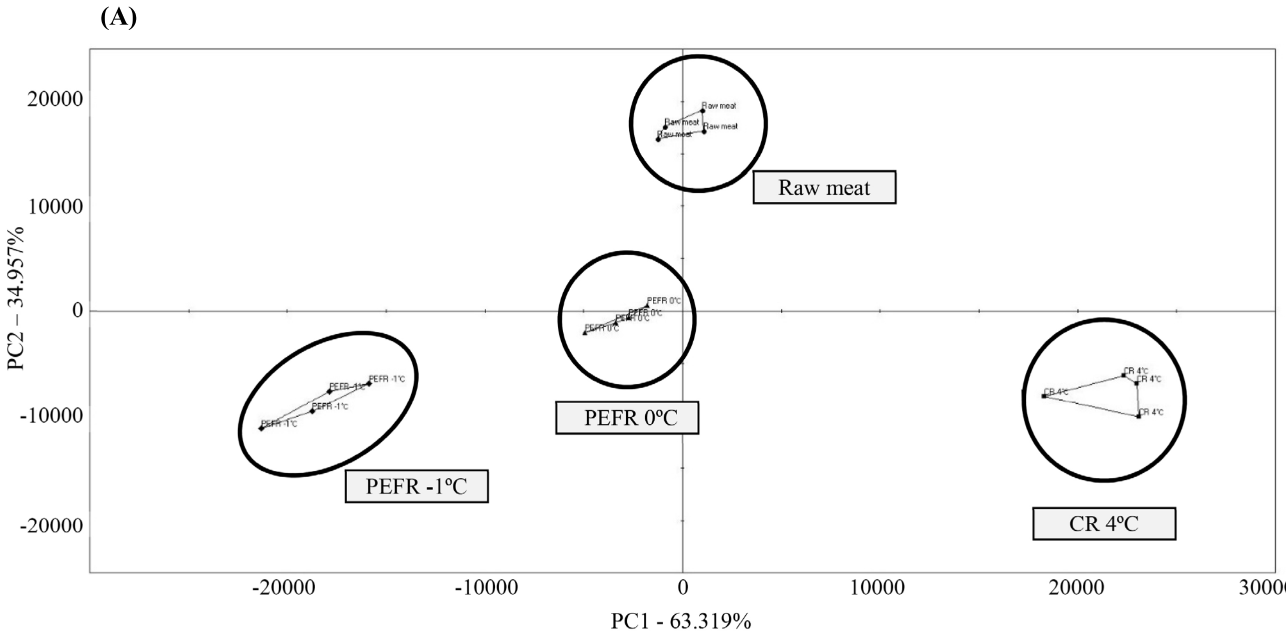
Electronic nose

Fig. 3 shows the results of electronic nose analysis after sous vide of wet-aged pork loin. The PCA results (Fig. 3A) showed that the contribution rate of principal component 1 (PC1, X-axis) was 61.996% and that of principal component 2 (PC2, Y-axis) was 36.203%. There was a clear difference in flavor between the wet-aged pork loin and raw meat samples after sous vide; there were also significant differences in flavor based on the aging conditions. The volatile compounds identified in the samples are summarized in Fig. 3B. Butan-2-one (butter), methyl acetate (fruity), dimethyl sulfide (sulfurous), hydroxy acetone (caramelized), 3-methylbutanal (toasted), pent-1-en-3-ol (milky), acetyl propionyl (creamy), *n*-butanol (cheese), pyrazine (roasted hazelnuts), ethyl butyrate (caramelized), and prenylthiol (smoky) were some of the identified volatile compounds with positive effects on the flavors of sous vide pork loin (Bassey et al., 2022). Volatile compounds with negative effects included ethanol (alcoholic), propanal (pungent), and furan (Bassey et al., 2022). Dimethyl sulfide (sulfurous), ethyl butyrate (caramelized), and prenylthiol (smoky) were detected at a higher level in the PEFR group than in the Raw meat and CR samples, and at the highest level in the PEFR –1°C samples. This shows that wet-aging using the PEFR had positive effects on the flavor of sous vide pork loin. Hydroxy acetone (caramelized), 3-methylbutanal (toasted),

Table 4. Weight loss of the sous vide pork loin and sous vide after wet-aging with different conditions

Traits	Raw meat	Wet-aging conditions			SEM
		CR (2 wk)	PEFR		
			0°C (3 wk)	–1°C (4 wk)	
Aging loss	-	10.02±0.72[a]	4.86±0.88[b]	4.85±0.38[b]	0.884
Cooking loss	22.36±2.62[b]	26.40±0.51[a]	23.95±0.94[b]	24.01±0.75[b]	0.564
Total loss	22.36±2.62[c]	36.41±1.16[a]	28.80±1.59[b]	28.86±0.10[b]	1.559

All values are expressed as mean±SE.
[a–c] Means in the same row with different letters are significantly different (p<0.05).
CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.



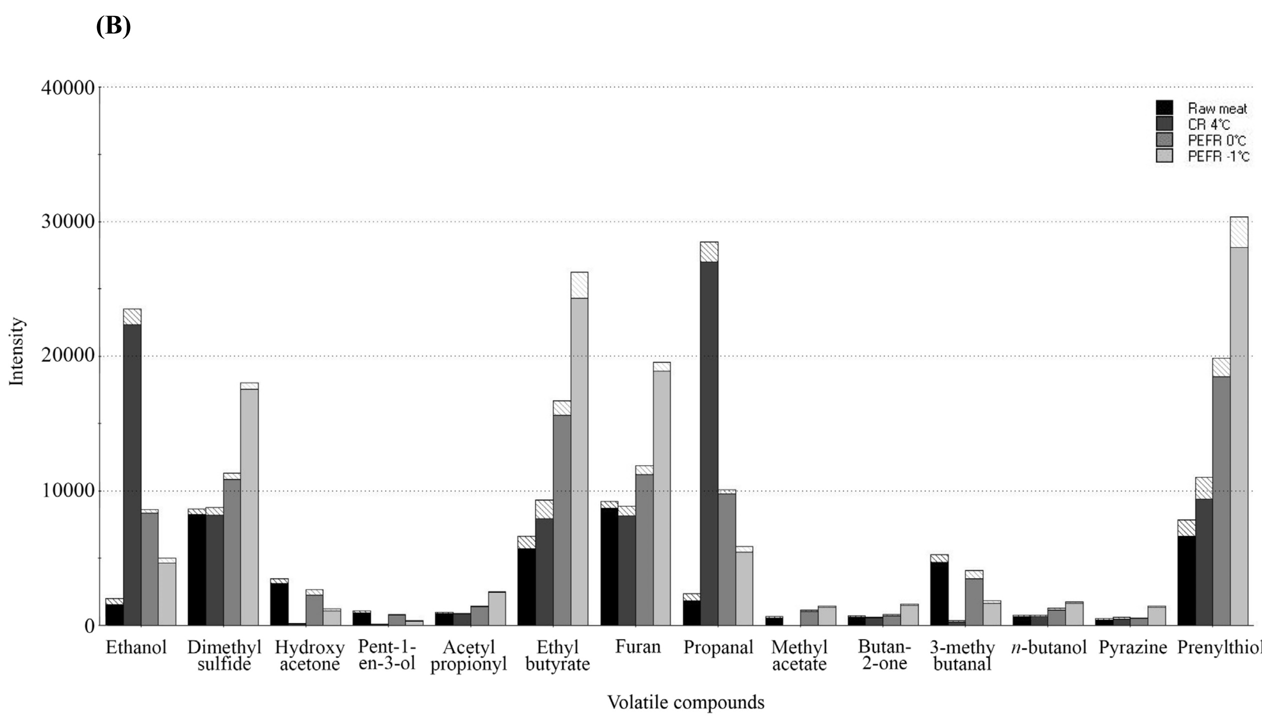


Fig. 3. Electronic nose data of the sous vide pork loin and sous vide after wet-aging with different conditions. (A) Principal component analysis plot of wet-aged and sous vide pork loin in a pulsed electric field system using flash gas chromatography electronic nose. (B) Main volatile compounds of wet-aged and sous vide pork loin in a pulsed electric field system using flash gas chromatography electronic nose. PC, principal component; PEFR, pulsed electric field refrigerator; CR, commercial refrigerator.

and pent-1-en-3-ol (milky) were detected at the highest level in the raw meat samples and at the lowest level in the CR samples. However, the rate of decrease in the levels of such volatile compounds was relatively low in the PEFR group than in the CR samples, showing that a PEFR may positively contribute to the flavor of sous vide pork loin. Higher levels of acetyl propionyl (creamy), methyl acetate (fruity), *n*-butanol (cheese), and pyrazine (roasted hazelnuts) were detected in the PEFR group than in the raw meat and CR samples, showing that wet-aging using a PEFR can enhance the positive flavor of sous vide pork loin. Higher levels of butan-2-one (butter) were detected in the PEFR –1℃ samples than in the other pork loin samples. This may be because the PEFR –1℃ samples were exposed to the longest period of aging. In addition, the previously observed decrease in the level of flavor compounds is supposedly because of a decrease in the Maillard reaction as the pH was lowered by the wet-aging process (Rannou et al., 2016). Similarly, Hwang et al. (2019) reported that aging of pork meat produces 3-methylbutanal and sulfur-containing compounds, and that such volatile compounds can enhance the flavor of the aged pork meat. Ethanol (alcoholic) and propanal (pungent) were detected at higher levels in the wet-aged group and CR samples than in the raw meat samples and PEFR group, respectively. It appears that wet-aging leads to the formation of negative flavor compounds, such as ethanol and propanol, and that the application of a PEFR to lower the temperature during wet-aging may help inhibit the formation of such compounds. Furan was detected at a higher level in the PEFR group than in the raw meat and CR samples. This may have been due to the formation of free radicals and hydrogen peroxide from unsaturated fatty acids because they were exposed to electric currents from PEF (Kantono et al., 2021). In this study, there was no improvement in the flavor of the CR samples, which were prepared by sous vide of regularly wet-aged pork loin. However, positive flavor compounds were produced and the formation of negative flavor compounds was inhibited upon the application of a PEFR to wet-aging. Hence, wet-aging using a PEFR appears to be suitable for preparing sous vide pork loin in terms of flavor.

Electronic tongue

Fig. 4 shows the results of electronic tongue analysis after sous vide of wet-aged pork loin. Sourness was higher in the wet-aged samples than in the raw meat samples and highest in the CR samples. Saltiness and umami were detected at a higher level in the wet-aged samples than in the raw meat samples; the PEFR 0℃ sample exhibited the highest level of umami. Kim et al. (2017) reported that the sourness that develops in wet-aged beef is due to the accumulation of lactic acid produced by lactic acid bacteria under anaerobic conditions. Therefore, wet-aging supposedly increased the sourness after sous vide of wet-aged pork loin; since excessive sourness can result in a peculiar taste, this factor should be considered when performing

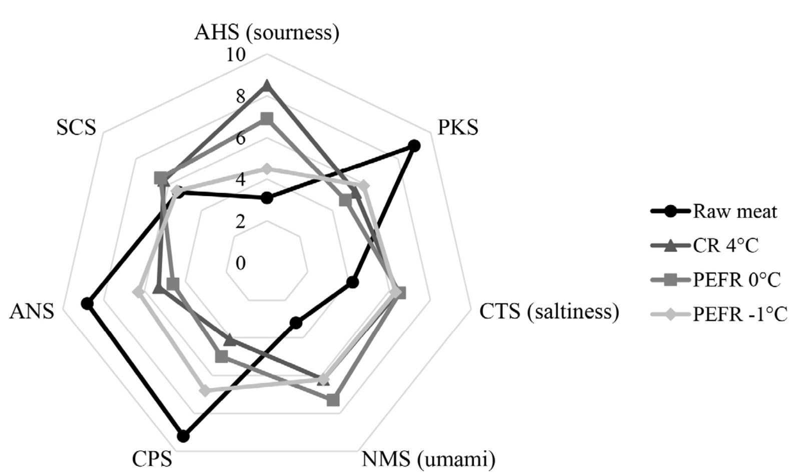


Fig. 4. Intensity comparison score radar chart of the sous vide pork loin and sous vide after wet-aging with different conditions using taste sensors electronic tongue. AHS, sourness; SCS, standard sensor; PKS, auxiliary sensor; ANS, auxiliary sensor; CTS, saltiness; CPS, standard sensor; NMS, umami; CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

wet-aging. Umami is considered the most important factor in sous vide cooking of meat, and nucleotide compounds and free amino acids (glutamic acid and aspartic acid) are the major precursors of umami (Ismail et al., 2022). The contents of the major precursors of umami, such as nucleotide compounds and free amino acids, increase as aging progresses (Hwang et al., 2019). Hence, applying wet-aging before sous vide cooking of pork loin can improve the taste and increase consumer preference.

Sensory evaluation

Table 5 shows the results of sensory analysis after sous vide of wet-aged pork loin. The score for color was significantly higher for the wet-aged group than for the raw meat samples ($p<0.05$). This result was due to the negative effects of high CIE L* on the perception of color (Ángel-Rendón et al., 2020). The score for taste was significantly higher for the PEFR 0°C samples than for the raw meat and CR samples ($p<0.05$). This appears to be due to the increase in the contents of nucleotide compounds and free amino acids during wet-aging of pork loin, as reflected in the electronic tongue analysis results (Lee et al., 2019). There was no difference in the scores for the CR and raw meat samples, despite the CR samples being wet-aged; this may have been due to the negative effects of excessive sourness on the taste (Terjung et al., 2021). Rancid and metallic flavors were significantly lower in the CR samples than in the PEFR 0°C samples ($p<0.05$). King et al. (2021) reported that rancid and metallic flavors of meat increase in intensity upon aging. Moreover, the results of electronic nose analysis showed that the CR samples had the highest levels of ethanol (alcoholic) and propanal (pungent), which also seem to have contributed to the aforementioned result. Flavor was significantly higher in the PEFR group than in the raw meat and CR samples ($p<0.05$). Electronic nose analysis also confirmed that there were more positive flavor compounds (i.e., 3-methylbutanal, etc.) in the PEFR group, and this appears to have affected the results of flavor assessment. Off-flavor was significantly lower in the raw meat and CR samples than in the PEFR 0°C sample ($p<0.05$), exhibiting a trend similar to that of rancid and metallic flavors. Nevertheless, the PEFR 0°C samples received higher ratings than the CR samples; this shows that wet-aging in a 0°C PEFR reduces the off-flavor after sous vide of pork loin. Moreover, since the PEFR 0°C group also received higher ratings than the raw meat samples, it appears that wet-aging of pork loin using a PEFR at 0°C can inhibit the formation of off-flavor

Table 5. Sensory evaluation of the sous vide pork loin and sous vide after wet-aging with different conditions

Traits	Raw meat	Wet-aging conditions			SEM
		CR (2 wk)	PEFR		
			0°C (3 wk)	–1°C (4 wk)	
Color	7.67±1.03^{b}	8.75±0.27^{a}	9.03±0.57^{a}	9.15±0.51^{a}	0.175
Taste	8.28±0.38^{c}	8.45±0.69^{bc}	9.05±0.68^{a}	8.82±0.58^{ab}	0.097
Rancid	8.75±0.76^{ab}	7.80±0.97^{b}	9.17±0.93^{a}	8.58±0.58^{ab}	0.188
Metallic	8.20±0.79^{ab}	7.50±1.22^{b}	9.00±1.07^{a}	8.38±0.44^{ab}	0.192
Flavor	8.22±0.44^{b}	8.29±0.67^{b}	9.00±0.92^{a}	8.93±0.51^{a}	0.101
Off-flavor	7.49±0.86^{b}	7.29±0.95^{b}	8.83±1.21^{a}	8.40±1.14^{ab}	0.233
Texture	7.93±0.80^{b}	8.50±0.63^{ab}	9.00±0.71^{a}	8.82±0.68^{a}	0.201
Overall acceptability	7.96±0.65^{b}	8.56±0.78^{ab}	9.00±0.76^{a}	8.97±0.77^{a}	0.123

All values are expressed as mean±SE.

$^{a–c}$ Means in the same row with different letters are significantly different ($p<0.05$).

CR, commercial refrigerator; PEFR, pulsed electric field refrigerator.

after sous vide. The score for texture was significantly higher for the PEFR group than for the raw meat samples ($p<0.05$). This is supposedly due to the higher water content and lower shear force of the raw meat samples than those of the PEFR group. Since consumers prefer tender and juicy meat, it can be assumed that applying a PEFR to wet-aging of pork loin before sous vide may increase consumer preference (Santos et al., 2021). Overall acceptability was significantly higher for the PEFR group than for the raw meat samples ($p<0.05$). Therefore, no improvements in sensory characteristics other than color can be expected from applying general wet-aging before sous vide of pork loin. However, applying wet-aging using a PEFR before sous vide of pork loin can improve the taste, flavor, off-flavor, texture, and overall acceptability compared with those of the raw meat and CR samples, and as a result, improve the sensory characteristics of sous vide pork loin.

Conclusion

This study showed that sous vide of pork loin wet-aged using a PEFR reduced the fat content and shear force, and increased the WHC before heating compared with those of raw meat samples. Sous vide of pork loin wet-aged using a PEFR can improve color stability and weight loss compared to CR samples. The electronic nose analysis showed that wet-aging of pork loin using PEFR enhanced the formation of positive flavor compounds and suppressed the formation of negative flavor compounds compared to CR samples. Electronic tongue analysis showed that wet-aging of pork loin increased the sourness, saltiness, and umami after sous vide. Sensory evaluation showed that wet-aging can improve the color of wet-aged pork loin after sous vide; for the various aspects of sensory evaluation, the PEFR 0℃ samples received higher ratings than the raw meat and CR samples. In conclusion, general wet-aging (CR) did not improve the quality of sous vide pork loin, whereas wet-aging using a PEFR improved multiple quality-related properties. Hence, wet-aging using a PEFR is suitable for the preparation of sous vide pork loin.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Acknowledgements

This study was supported by the Basic Science Research Program of the National Research Foundation of Korea (NRF), which is funded by the Ministry of Education (2018R1D1A1B07049938).

Author Contributions

Conceptualization: Kim HY. Data curation: Park SY. Formal analysis: Go HY. Methodology: Go HY, Park SY. Software: Go HY. Validation: Park SY. Investigation: Go HY. Writing - original draft: Go HY. Writing - review & editing: Go HY, Park SY, Kim HY.

Ethics Approval

Sensory evaluation of this study was approved by the Kongju National University's Ethics Committee (Authority No:

KNU_IRB_2022-083).

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