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Research Article

The Physicochemical and Sensory Properties of Whey-Fed Pork Loin after Salting, Dry Aging, and Sous Vide Cooking

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This study was conducted to evaluate the physicochemical properties of whey-fed pork loin subjected to salting, dry aging, and sous vide cooking. We compared raw and treated pork loin from pigs fed a basal diet (control) and those fed a diet supplemented with whey powder. Treated pork was salted, dry aged for 0–30 d, and then cooked using sous vide. The crude fat, total lipid, and cholesterol content and shear force of raw whey powder-fed pork loin were significantly lower than those of the control, while the crude protein content was higher. Cooking loss, hardness, and gumminess were found to decrease with the aging period in sous vide-treated pork. Dietary supplementation with whey had positive effects on pork color stability, texture, and sensory evaluation, and it significantly inhibited the growth of bacteria. The results suggest that supplementing the diet of pigs with whey powder can enhance meat quality, especially when combined with salting, dry aging, and sous vide cooking.

1. Introduction

Animal protein consumption has increased in recent years, especially the consumption of meat, and this trend is likely to continue [1, 2]. The intake of saturated fatty acids from animal products is associated with an increased risk of cardiovascular disease. Hyperlipidemia and high concentrations of cholesterol are major risk factors leading to arteriosclerosis, myocardial infarction, and cerebral infarction [3]. Therefore, many consumers are trying to reduce their fat intake [1, 4]. Consumers concerned about health and nutrition show a preference for low-calorie and low-fat products. However, fat is an important component contributing to the flavor, juiciness, and water-holding capacity of meat products, all of which influence the palatability of meat. A reduction in the fat content can result in bland, hard, dry, and crumbly meat products [5, 6]. Feed additives can have direct effects on meat traits such as tenderness, juiciness, and flavor [7]. To meet consumer expectations, the addition of natural substances to animal diets to produce healthier meat products has gained increasing attention.

Whey is a major by-product of cheese manufacturing and considered a waste product, which can cause ecosystem pollution [8]. However, whey protein has high nutritional value and contains a mixture of proteins, growth factors, and biologically active compounds [9]. The branched chain amino acids in whey can improve muscle protein anabolism and help lipid metabolism and some chronic metabolic diseases [10, 11]. Whey protein supplements improve mineral absorption and protein synthesis and have beneficial effects on cardiovascular risk, blood lipids, insulin, and glycaemia [12]. In addition, clinical evidence indicates that intake of whey protein supplements can reduce postprandial and fasting triglyceride and cholesterol levels and atherogenic index values [3, 13].

There are many ways to process meat, which can affect meat quality. Sous vide is a method of slow cooking, using a food-grade vacuum bag in a water bath, which helps food retain its taste and aroma and enables very precise control over cooking [14]. Cooking meat using controlled heating facilitates the retention of color, flavor, and quality by minimizing moisture or mass loss due to separation [14, 15]. Control over the heat intensity, processing time, and storage conditions can improve the shelf life of products by limiting cross-contamination during storage and providing protection from microorganisms [16, 17]. Sous vide also prevents lipid oxidation and protein damage and improves the tenderness, juiciness, and texture of meat [15, 18]. Dry aging is a traditional process that involves drying without packing at refrigerated temperatures. Dry aging can increase the palatability of meat, particularly the flavor, taste, and tenderness [19, 20]. Moreover, it has been reported that dry aging is associated with improved water-holding capacity. The proteolytic degradation of cytoskeletal proteins and subsequently expanded myofibrils retains more myowater in the meat structure [21].

To the best of our knowledge, no studies to date have been conducted to determine the effects of salting and dry aging on the meat quality of whey-fed pork, especially when combined with sous vide cooking. Therefore, the objective of this study was to examine the effects of whey feeding on the quality of raw pork loin and then evaluate the effects of combinations of processing methods on the physicochemical properties of whey-fed pork loin.

2. Materials and Methods

2.1. Sample Preparation. A total of 40 pork loins from 20 crossbred (Duroc × Landrace × Yorkshire) pigs (average live weight of 120 kg) were obtained from a farm located in Gyeonggi-do (Noh Hayeong farm, Gyeonggi-do, Korea). The procedure for animal care and use were in accordance with the guidelines of the Konkuk University Ethics Committee. Ten pigs were fed a basal diet (control group). The diets of the other 10 animals were supplemented with whey powder (Samik Dairy Co., Ltd., Seoul, Korea) at a concentration of 1 g/kg of the basal diet. After removing the exterior fat and visible connective tissue from the surface, each pork loin was divided in half for a total of 80 loin sections. Forty loin sections from control pigs were randomly allocated to four treatments ($n = 10$ loin sections/treatment), which included one raw meat group (RC) and three dry-aged, sous vide-cooked control diet pork loin groups (ASC0, ASC15, and ASC30); the 40 loin sections from whey-fed pigs were allocated in the same manner (1 × RW, 3 × ASW : ASW0, ASW15, ASW30). The raw meat samples were stored in a −80°C deep freezer until further analysis. Before dry aging, the samples were rubbed with 5% (w/w) sun-dried salt for 2 d. After salting, any excess salt was wiped off, and the samples were washed with tepid water. Samples were hung in a refrigerated room at 1 ± 0.5°C and relative humidity of 80 ± 5% for 0–30 d (depending on the dry aging treatment). Subsequently, the meat samples were cut into 100 ± 5 g cubes, placed in pouches, and sealed using a vacuum packer (FJ500XL, Fujoo, Korea) for sous vide cooking. According to the methods of del Pulgar et al. [22], the meat was heated at 60°C for 3 h, followed by cooling below 4°C.

2.2. Lipid Analysis. Lipid extraction was performed following the modified method presented by Folch et al. [23]. In brief, the sample was extracted using a homogenizer stirrer (HS-30E, Daihan Scientific Co., Ltd.) with saturated sodium chloride (NaCl) and chloroform : methanol (2 : 1 v/v). After shaking, the mixture was centrifuged using a refrigerated centrifuge (Sorvall RC-3; Thermo Fisher Scientific, Waltham, MA, USA) at 3,000 rpm at 4°C for 20 min, to separate the sample. Next, the lipid phase was evaporated using nitrogen gas and the dried lipids were weighed.

2.3. Cholesterol Content. Cholesterol content was assayed according to the methods of Mannheim [24]. 2.5 g pork loin sample with 1 g sea sand, 20 mL 1 M methanolic potassium hydroxide solution, and 10 mL isopropanol were placed in a round-bottomed flask and heated under a reflux condenser for 30 min. After cooling, the supernatant solution was transferred to a 25 mL volumetric flask. The residue was boiled twice under a reflux condenser with 6 mL isopropanol for 5 min. Solutions were collected in the volumetric flask and diluted with isopropanol to the 25 mL mark. The solution was then filtered through Whatman No. 2 paper and assayed with a commercial analysis kit (Cat. Boehringer Mannheim, Germany).

2.4. Proximate Composition. The moisture, ash, crude protein, and fat content of samples were determined using the official methods of AOAC International (AOAC, 2012) [25].

2.5. pH. A 2 g sample was homogenized for 60 s with 18 mL of distilled water in a bag mixer 400 (Interscience, Woburn, MA, USA). The pH values for each sample were measured using a pH meter (pH 900, Precisa Gravimetrics AG, Dietikon, Switzerland).

2.6. Expressible Drip. Expressible drip was measured according to the methods of Benjakul et al. [26]. A 0.3 g sample was weighed (A) and placed between two pieces of filter paper (Whatman No. 1). The sample was then pressed using a force meter at 9.9 kg/cm^2 force for 30 s. The sample was removed and reweighed (B). The expressible drip was calculated using the following equation:

expressible drip (%) = (weight of A − weight of B)/weight of A × 100.

2.7. Cooking Loss. To evaluate the cooking loss of raw meat, each sample was weighed and cooked individually in a plastic bag in a water bath at 75°C until the core temperature reached 70°C. The core temperature was monitored using a digital thermometer (Testo 108, Testo SE and Co. KGaA, Lenzkirch, Germany) inserted into each sample. To evaluate sous vide samples, each sample was weighed and heated at 60°C for 3 h. All cooked samples were cooled to room temperature and reweighed after surface moisture was removed. Cooking loss of the meat was calculated using the following equation:

cooking loss (%) = (sample weight before cooking–sample weight after cooking)/sample weight before cooking × 100.

2.8. WarnerBratzler Shear Force and Texture Profile Analysis. The samples used for measurement of cooking loss were placed in a texture analyzer (CT3-1000, Brookfield Engineering Laboratories, Inc., Middleboro, MA, USA). Warner–Bratzler shear force was measured by positioning the sample horizontally using a bladelike probe (TA-SBA). Texture profiles of hardness, cohesiveness, springiness, gumminess, and chewiness were measured by two consecutive compressions using a cylindrical probe (TA 418). The conditions for the analysis are shown in Table 1.

2.9. Color Measurements. The sample color was determined using a colorimeter (NR-300, Nippon Denshoku, Tokyo, Japan). The instrument was calibrated prior to taking measurements using a standard white plate supplied with the instrument (CIE $L^* = +97.83$, CIE $a^* = -0.43$, and CIE $b^* = +1.98$). Values for CIE L^* (lightness), CIE a^* (redness), and CIE b^* (yellowness) were recorded.

2.10. Sensory Evaluation. Sensory tests were conducted on the control pork loin and sous vide-cooked whey-fed pork loin after 30 d of dry aging. Sensory evaluation was performed by 10 trained panelists (male and female; mean age, 26.6 years) from the Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul, Korea with basic knowledge of, and adequate experience in, sensory evaluation of meat quality. Each panelist was offered two white plates with $2.5 \times 2.5 \times 0.5\,\mathrm{cm}^3$ meat samples at 25°C. Panelists rinsed their mouth with fresh water and were allowed 1–2 min breaks before evaluating new samples. A seven-point hedonic scale was used for each sensory parameter: hardness (1 = soft to 7 = tough), juiciness (1 = dry to 7 = juicy), flavor (1 = undesirable to 7 = desirable), color (1 = undesirable to 7 = desirable), taste (1 = undesirable to 7 = desirable), and overall acceptability (1 = undesirable to 7 = desirable).

2.11. Microbiology. 25 g sample and 225 mL of sterilized 0.85% NaCl solution were placed in a bag mixer 400 (Interscience, Woburn, MA, USA) and homogenized for 1 min. Microbiological analysis of samples was performed using 3 M Petrifilm (3M, St. Paul, MN, USA). The bacterial count was determined after selecting 30–300 clusters per plane following incubation for 48 h at 37°C, and coliform and *Escherichia coli*/coliform plates were incubated for 24–48 h at 37°C. The microbial counts were expressed as log colony-forming units/g (Log CFU/g).

2.12. Statistical Analysis. The experimental design included eight treatments (two raw pork loins: RC and RW, and six salted, dry-aged, and sous vide-cooked pork loins: ASC and ASW) allocated to the sections of paired pork loins from 20 carcasses ($n = 10$; 20 carcasses × 2 loins × 2 sections = 80 sections for 8 treatments). The raw pork loin data and sensory test data were analyzed using t tests with SPSS 24.0 software (SPSS Inc., Chicago, IL, USA). The dry aging and sous vide pork loin data were analyzed by two-way ANOVA using Tukey's test with SPSS 24.0 software (SPSS Inc.). Results with p values < 0.05 were considered significant.

3. Results and Discussion

3.1. Total Lipid and Cholesterol Content. Dietary supplementation with whey powder had a significant effect on the total lipid and cholesterol content of pork (Table 2). The RW group had significantly lower ($p < 0.05$) total lipid and cholesterol content than the RC group. This observation was similar to that reported by Rakvaag et al. [13], who investigated reductions in cholesterol level after whey protein consumption by adults and concluded that whey protein may exert a metabolic effect via its insulinotropic property. Swiatecka et al. [27] also reported that whey protein supplementation decreased cholesterol levels in mouse blood. Furthermore, whey protein contains angiotensin-converting enzyme inhibitors, lactalbumin, lactoglobulin, and and essential amino acids, such as valine, leucine, and isoleucine, which promote lipid metabolism and exert hypotriacylglycerolemic and cholesterol-lowering effects. Thus, whey protein may play a role in weight control and metabolism [3, 10, 28]. High cholesterol is the main factor leading to arteriosclerosis and cardiovascular disease. Intake of whey protein can reduce the content of lipid and cholesterol. Therefore, whey feeding has a beneficial effect on improving meat quality, and it lays the foundation for further research and development of meat products.

3.2. Proximate Analysis, pH, Expressible Drip, and Cooking Loss. The proximate composition and physicochemical characteristics of the pork loin samples are shown in Tables 2 and 3. No significant differences in the moisture and ash content of raw pork loin were found between RC and RW groups ($p > 0.05$). However, significant effects on moisture were detected ($p < 0.001$) in the dry-aged and sous vide-treated pork loin (Table 3). As the aging time increased, the moisture content of all samples significantly decreased; however, the moisture content of the ASW group was always significantly higher than that of the ASC group due to its higher pH values and protein content. In meat, the myofibrillar protein network surrounds water molecules; therefore, high protein content can help to retain more moisture [21]. This result was expected given that the surface area of the dry-aged pork loin was directly exposed to air. Similar results were reported by Lee et al. [29]. In their study, when the surface of the pork loin was exposed to air during dry aging, the moisture evaporated, resulting in decreased moisture content. The whey powder-supplemented group had a significantly higher protein and lower fat percentage in both raw and treated pork loin. An increase in protein content was also reported by Ha et al. [30]. Whey protein can promote whole body and muscle protein synthesis due, in part, to the fact that casein in whey protein can regulate insulin secretion and reduce lipogenesis [31]. Similar results have been reported in previous studies. Belobrajdic et al. [32] found that dietary supplementation with whey protein concentrate reduced the body weight of rats. The amount of

Table 1: Instrumental conditions of the texture analyzer.

Item	Shear force	Texture
Sample size	4.00 × 1.00 × 1.00 cm	2.00 × 2.00 × 2.00 cm
Probe	TA-SBA	TA418 (sphere 12.7 mmD)
Target value	15.0 mm	10.0 mm
Trigger load	500 g	10 g
Test speed	2.50 mm/s	1.00 mm/s

Table 2: Total lipid content (%), cholesterol content (mg/100 g), proximate analysis (%), pH, expressible drip (%), and cooking loss (%) of raw pork loin.

Treatment	RC	RW	SEM	p value
Total lipid	2.66[a]	2.43[b]	0.06	0.05
Cholesterol	59.19[a]	53.42[b]	1.54	0.05
Moisture	73.34	73.44	0.358	0.795
Ash	1.26	1.25	0.033	0.775
Crude protein	23.22[b]	24.78[a]	0.115	0.001
Crude fat	0.95[a]	0.79[b]	0.038	0.05
pH	5.72	5.75	0.013	0.107
Expressible drip	41.93	40.08	1.013	0.106
Cooking loss	29.20[a]	27.52[b]	0.595	0.05

RC, raw control diet pork loin; RW, raw whey-fed pork loin. SEM : standard error of the mean. [a,b]Means within a row with different letters are significantly different ($p < 0.05$).

subcutaneous and carcass fat in rats fed the concentrate was lower than that of rats fed red meat [33]. Moreover, whey protein decreased the fat mass of animals with diet-induced obesity, while increasing the lean mass [27]. Whey protein is rich in arginine and lysine, which can enhance anabolic or muscle growth hormone production, reduce fat content, and stimulate muscle growth [34]. Both ash and crude protein content increased with the aging period ($p < 0.001$). These results are in accordance with those obtained by Lee et al. [29], who showed that increases in ash and protein content were due to a relative reduction in moisture percentage. These results indicate that whey powder supplementation in the diet of pigs has a significant beneficial effect on pork loin meat quality.

pH plays an important role in the water-holding capacity and color of meat. The pH value (Table 3) of dry-aged pork loin significantly increased with the dry aging period ($p < 0.001$). This can be attributed to an increase in alkaline-free amino acids generated during the process of protein hydrolysis by endogenous proteinases in meat [35]. Previous studies reported that dry-aged pork loin had a significantly higher pH than the control, and the pH of Hanwoo strip loin increased during dry aging [29, 36]. The raw pork loin from whey-fed pigs showed lower cooking loss than control ($p < 0.05$) (Table 2). The expressible drip and cooking loss of ASW were also significantly lower than those of ASC ($p < 0.05$; Table 3 and Figure 1). Cooking loss and expressible drip are related to the water-holding capacity of meat, and the results can be attributed to the ability of whey to retain water, which promotes higher pH values and protein content in ASW meat than in ASC meat. Del Pulgar et al. [22] reported similar results, where sous vide cooking resulted in lower water loss than conventional cooking. This is most likely due to the vacuum packaging used for sous vide cooking at 60°C, which prevents the loss of free water [37]. The pH of pork was inversely related to its cooking loss. The lower cooking loss and expressible drip in the ASW group indicate that at higher pH values, pork loin can improve the water-holding capacity of meat. As the pH is close to the isoelectric point of the myofibrillar protein, the binding force between the myofibrillar protein and water molecules decreased, resulting in a reduction in the water-holding capacity of meat [38]. Moreover, cooking loss decreased with aging duration ($p < 0.001$; Figure 1) due to the gradual evaporation of moisture during dry aging. In addition, dry aging improved the water-holding capacity. The distribution of water in meat is associated with the myofibrillar protein network structure. Proteolytic degradation of cytoskeletal proteins with aging enables the swelling of myofibrils, which contributes to water retention [21, 39]. This phenomenon is simultaneously combined with the sous vide processing method to maximize the retention of gravy, thereby improving the palatability of meat.

3.3. Color. Color is an important parameter of meat quality. Meat color depends on the pre-rigor temperature, aging time, oxygen consumption rate, and metmyoglobin content [40, 41]. The color results for raw and treated pork loin are presented in Tables 4 and 5. The CIE L^* and CIE b^* values of raw meat showed no significant differences ($p > 0.05$) between treatments. The CIE a^* of the whey-fed pork loin was significantly higher ($p > 0.05$) than that of the control, in both raw and aged, sous vide-cooked meat. A significant interaction between treatment and dry aging on redness and yellowness was observed, and pork loin was more affected by dry aging ($p > 0.05$). During dry aging, the CIE a^* and CIE L^* values tended to decrease; however, CIE b^* values increased. Color is related to the moisture content of meat. Moisture causes light refraction, and after dry aging, the moisture content on the loin surface decreases, resulting in decreases in CIE L^* and CIE a^* values [42]. However, the lightness and redness values of the ASW group were always significantly higher than those of the ASC group during the aging period, and due to the interaction between whey feeding and dry aging, the moisture content of the ASW group was higher than that of the control group. Moreover, previous studies demonstrated that meat from whey-fed pigs had higher redness values and iron content than meat from control pigs, and the redness of meat showed a close relationship with iron content [43, 44]. Therefore, whey feeding can delay color darkening caused by dry aging and has a beneficial effect on color stabilization. In addition, the redness of cooked meat is inversely proportional to the degree of myoglobin degeneration. Heat treatment causes the degradation of myoglobin in meat. The degree of degradation of myoglobin increases with increasing temperature [45]. Sous vide is a method of slow cooking under low temperature that can reduce the degradation of myoglobin and increase its thermal stability. Vaudagna et al. [46] also found that the oxidation of myoglobin was limited by sous vide cooking. Therefore, although redness decreased, the

Table 3: Proximate analysis (%), pH, and expressible drip (%) of dry aged, sous vide-cooked pork loin from pigs fed a whey powder-supplemented diet.

Items		Moisture	Ash	Crude protein	Crude fat	Expressible drip	pH
Treatment							
ASC		65.96	2.24	27.39	2.55	32.63	5.85
ASW		67.91	2.21	28.43	2.29	31.16	5.88
SEM		0.154	0.039	0.123	0.082	0.407	0.010
p value		<0.001	0.605	<0.001	<0.05	<0.05	<0.05
Aging (d)							
0		69.20[a]	1.48[b]	26.95[b]	2.50	32.33	5.75[c]
15		67.59[b]	1.39[b]	27.47[b]	2.42	31.90	5.88[b]
30		64.00[c]	3.82[a]	29.30[a]	2.35	31.46	5.96[a]
SEM		0.188	0.047	0.151	0.101	0.499	0.012
p value		<0.001	<0.001	<0.001	0.551	0.489	<0.001
Treatment × aging interaction							
	×0	67.70	1.46	26.45	2.61	<33.15	5.74
ASC	×15	67.70	1.39	26.91	2.56	32.72	>5.85
	×30	62.48	3.88	28.80	2.49	32.03	5.94
	×0	70.71	1.49	27.46	2.40	31.51	5.76
ASW	×15	67.49	1.39	28.02	2.28	31.07	5.91
	×30	65.51	3.76	29.80	2.20	30.90	5.98
SEM		0.266	0.067	0.214	0.142	0.705	0.017
p value		<0.001	0.547	0.964	0.947	0.915	0.633

ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked whey-fed pork loin. SEM : standard error of the mean. [a-c]Means within the same column with different letters are significantly different ($p < 0.05$).

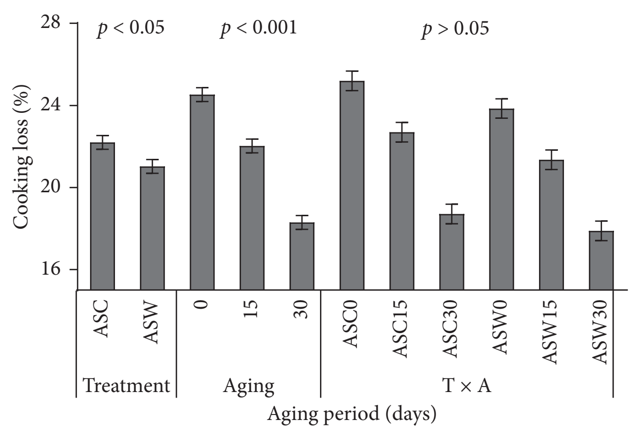

Figure 1: Effect of cooking loss (%) in dry-aged, sous vide-cooked whey-fed pork loin. (1) ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked, whey-fed pork loin; ASC0, 0 d dry-aged, sous vide-cooked control diet pork loin; ASC15, 15 d dry-aged, sous vide-cooked control diet pork loin; ASC30, 30 d dry-aged, sous vide-cooked control diet pork loin; ASW0, 0 d dry-aged, sous vide-cooked whey-fed pork loin; ASW15, 15 d dry-aged, sous vide-cooked whey-fed pork loin; ASW30, 30 d dry-aged, sous vide-cooked whey-fed pork loin. (2) $T \times A$ treatment × aging interaction. Error bars indicate SEM.

decline was slower in ASW meat than in ASC meat. These results indicate that whey powder has a certain protective effect on the color stability of pork after dry aging and sous vide cooking.

3.4. Shear Force and Texture Profile. The shear force of raw pork loin and the texture properties of dry-aged, sous vide-cooked pork loin are shown in Tables 4 and 6. Shear force is a good way to measure initial tenderness. The shear force of RW was significantly lower than that of RC ($p < 0.05$), confirming that whey feeding can improve the tenderness of pork loin. This may be because whey feeding increased protein content in the RW group, thereby increasing amino acid content. Reportedly, amino acids can improve the water retention capacity and texture of meat [47]. Therefore, the whey-fed pork loin showed lower shear force than the control group. Texture analysis provides detailed information on texture characteristics, and further texture profile analysis was performed on salted, dry-aged, sous vide-cooked samples. We know that sous vide cooking can have beneficial effects on food qualities such as texture and tenderness [18]. Single-stage sous vide cooking of beef muscle decreased shear force [48]. In the present study, hardness, gumminess, and chewiness in the ASW group were significantly lower than those in the ASC group, and

Table 4: Shear force and color (CIE) of raw pork loin from pigs fed a whey powder-supplemented diet.

Treatment	RC	RW	SEM	p value
CIE L^*	54.90	53.52	1.268	0.334
CIE a^*	7.63^{b}	8.66^{a}	0.275	<0.01
CIE b^*	8.95	8.63	0.504	0.552
Shear force (kg)	3.43^{a}	3.09^{b}	0.126	<0.05

RC, raw control diet pork loin; RW, raw whey-fed pork loin. SEM: standard error of the mean. $^{a,\ b}$Means within a row with different letters are significantly different ($p < 0.05$).

Table 5: Color of dry-aged, sous vide-cooked pork loin in pigs fed a whey powder-supplemented diet.

Items		CIE L^*	CIE a^*	CIE b^*
Treatment				
ASC		71.12	4.96	8.64
ASW		71.87	5.55	8.29
SEM		0.201	0.033	0.132
p value		<0.05	<0.001	0.084
Aging (d)				
0		72.38^{a}	5.54^{a}	7.86^{b}
15		71.61^{a}	5.19^{b}	8.46^{ab}
30		70.48^{b}	5.03^{c}	9.07^{a}
SEM		0.246	0.041	0.161
p value		<0.01	<0.001	<0.01
Treatment × aging interaction				
	×0	72.29	5.16	7.69
ASC	×15	71.00	4.98	8.53
	×30	70.05	4.73	9.69
	×0	72.47	5.92	8.03
ASW	×15	72.21	5.41	8.39
	×30	70.92	5.33	8.44
SEM		0.348	0.057	0.228
p value		0.356	<0.05	<0.05

ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked whey-fed pork loin. SEM: standard error of the mean. $^{a\text{-}c}$Means within the same column with different letters are significantly different ($p < 0.05$).

these findings were consistent with the shear force results. An interaction effect of treatment and aging on hardness and gumminess was shown ($p < 0.05$); hardness and gumminess significantly decreased with aging in both dietary groups. However, the values for ASW were always lower than those for ASC. During the cooking process, heating increases the toughness of meat due to collagen shrinkage [49]. Proteolysis affects the tenderness and water retention capacity of meat. Crude protein content in the ASW group was higher than that in the ASC group, which may lead to higher levels of some proteases such as cathepsin. Cathepsin is released during meat aging and cooking, and the activity of cathepsin has a strong negative correlation with shear force [50–52]. The activity of cathepsin gradually decreases with increasing temperature [50, 53]. Therefore, in this study, the use of the sous vide cooking method to create a relatively low temperature environment can maintain high cathepsin activity. Thus, there was a synergistic interaction between whey feeding and dry aging, and subsequent treatment with sous vide processing had a positive effect on reducing the hardness and improving the texture of the meat. Hayes et al. [54] also reported improved texture properties after the addition of a whey protein fraction with minerals in meat products. It has been reported that aging weakens the muscle myofibrillar structure of meat so that the tenderness and texture of meat improve [55]. Moreover, the hardness value of the ASW group was significantly lower than that of the ASC group, which can be attributed to the higher pH of the ASW group during aging. Calpain is currently believed to play a major role in the proteolysis of cytoskeletal proteins, such as nebulin and titin, resulting in tenderization [56, 57]. Since calpain is maximally active at a neutral pH, the higher pH of the ASW group is beneficial to improve the activity of calpain, thereby reducing meat toughness. These results are in agreement with those obtained by Lee et al. [29], who also found that the hardness, gumminess, chewiness, and resilience were significantly lower in dry-aged pork loin than in a control. Berger et al. [58] also noted that dry aging could improve the quality of beef loin. These results indicate that the interaction of whey powder-supplemented diet and dry aging has beneficial effects on meat texture, especially combined with sous vide processing.

3.5. Sensory Evaluation. The outcomes of sensory evaluation of sous vide-cooked control pork loin and whey-fed pork loin aged for 30 d are summarized in Figure 2. No significant differences were observed in color or flavor between ASC and ASW groups; however, both presented high flavor scores owing to an increase in the concentration of certain meat constituents, resulting from the loss of moisture during dry aging, consistent with the observed improvement in the flavor of dry-aged beef [58]. The content and composition of various flavor precursors change during dry aging, imparting the meat with a unique flavor, such as a brown-roasted flavor [29]. Juiciness, taste, and overall acceptability scores of the ASW group were significantly higher than those of the ASC group ($p < 0.05$), probably because of higher moisture content and lower cooking loss in the ASW group. Dry-aged, sous vide-cooked whey-fed pork loin had a higher score for taste than the control, probably owing to the higher crude protein content in ASW. The intensity of taste is related to umami. A whey powder-supplemented diet can increase the crude protein content of meat, which is positively correlated with the umami flavor [59]. Moreover, it has been reported that, during dry aging, the content of umami compounds, such as glutamic acid and 5′-inosine monophosphate, increases [60]. Therefore, the interaction between whey feeding and dry aging helped the ASW group to obtain a higher taste score than the ASC group. Furthermore, the hardness of the ASW sample was significantly lower than that of ASC samples, consistent with the results of texture analysis. Dry aging weakens the myofibrillar structure, the minerals in whey powder can improve structural properties, and the sous vide cooking method is beneficial to increase tenderness, thereby decreasing meat hardness [15, 54, 55]. Accordingly, compared to the ASC group, the sensory qualities of 30-day dry-aged, sous vide-cooked pork loin in the ASW group were more favorable.

Table 6: Texture profile analysis of dry-aged, sous vide-cooked pork loin in pigs fed a whey powder-supplemented diet.

Items		Hardness (N)	Springiness (cm)	Chewiness (N•cm)	Gumminess (N)	Cohesiveness
Treatment						
ASC		24.31	0.80	10.32	13.96	0.54
ASW		21.44	0.79	9.06	11.10	0.54
SEM		0.300	0.014	0.275	0.313	0.014
p value		<0.001	0.610	<0.01	<0.001	0.654
Aging (d)						
0		24.61^{a}	0.72^{b}	9.75	14.25^{a}	0.55
15		22.36^{b}	0.84^{a}	9.83	12.12^{b}	0.54
30		21.65^{b}	0.84^{a}	9.49	11.22^{b}	0.53
SEM		0.368	0.017	0.337	0.384	0.017
p value		<0.001	<0.001	0.770	<0.001	0.688
Treatment × aging interaction						
	×0	26.76	0.74	10.93	16.55	0.56
ASC	×15	23.01	0.83	10.29	12.87	0.55
	×30	23.15	0.84	9.74	12.45	0.52
	×0	22.46	0.70	8.56	11.95	0.54
ASW	×15	21.71	0.84	9.36	11.37	0.52
	×30	20.15	0.84	9.25	9.99	0.54
SEM		0.520	0.024	0.476	0.543	0.024
p value		<0.05	0.473	0.159	<0.05	0.643

ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked whey-fed pork loin. SEM: standard error of the mean. [a-b]Means within the same column with different letters are significantly different ($p < 0.05$).

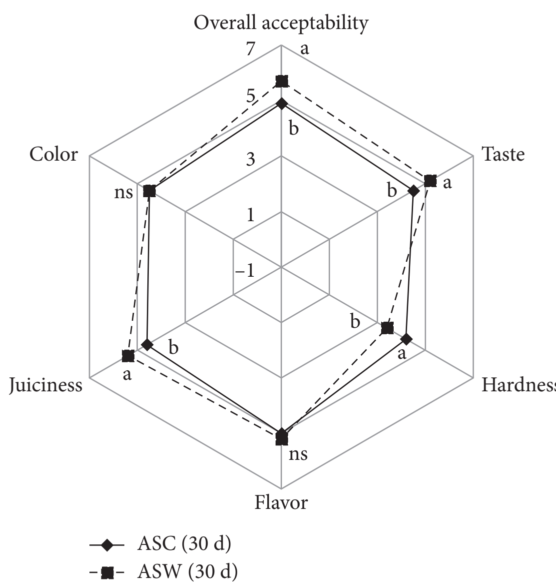

Figure 2: Sensory evaluation of dry-aged, sous vide-cooked pork loin obtained from pigs fed a whey powder-supplemented diet. ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked whey-fed pork loin. Means with different labels (a, b) differ significantly ($p < 0.05$).

3.6. Microbiological Evaluation. The results of the microbiological evaluation of dry-aged, sous vide-cooked whey-fed pork loin are shown in Figure 3. The number of total bacteria in both ASC and ASW slightly increased with dry aging time ($p < 0.001$). No *E. coli* and coliform bacteria were detected. These results demonstrate the importance of diet and dry aging in microbiological analyses in dry-aged, sous vide-cooked pork loin ($p < 0.01$). A similar trend was observed by Holmer et al. [61], who found that, as the duration of aging increased, aerobic plate counts increased. Although bacteria increased with aging, the magnitude of increase was small. Significantly lower amounts of bacteria were observed in the ASW group than in the ASC group, which could be because the dry aging process produces a dehydrated lean surface, and the low water activity of the sample and low temperature in the dry aging room may inhibit the growth of aerobic bacteria [58, 62, 63]. In addition, the slight increase in number of bacteria through 0–30 d indicates that sous vide cooking has a certain auxiliary effect on preventing bacterial growth. Diaz et al. [64] also confirmed that even

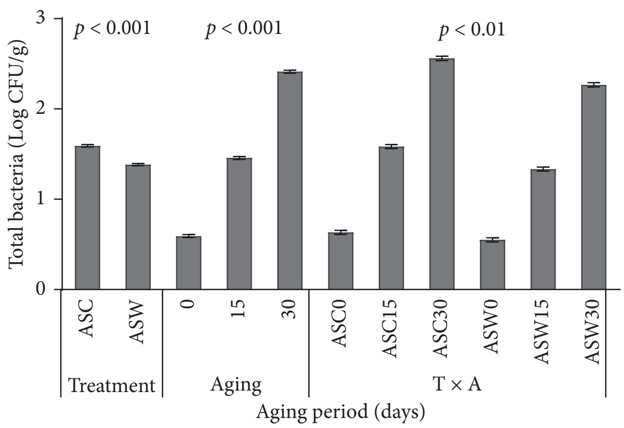

FIGURE 3: Effects of dry aging and sous vide cooking on the number of bacteria (Log CFU/g) in dry-aged, sous vide-cooked whey-fed pork loin. 1) ASC, dry-aged, sous vide-cooked control diet pork loin; ASW, dry-aged, sous vide-cooked, whey-fed pork loin; ASC0, 0 d dry-aged, sous vide-cooked control diet pork loin; ASC15, 15 d dry-aged, sous vide-cooked control diet pork loin; ASC30, 30 d dry-aged, sous vide-cooked control diet pork loin; ASW0, 0 d dry-aged, sous vide-cooked whey-fed pork loin; ASW15, 15 d dry-aged, sous vide-cooked whey-fed pork loin; ASW30, 30 d dry-aged, sous vide-cooked whey-fed pork loin. 2) $T \times A$ treatment × aging interaction. Error bars indicate SEM.

after 10 weeks of storage at 2°C, sous vide cooking ensured a very low level of microbial spoilage in pork loin.

Furthermore, whey feeding can improve dietary yeast content. Among the various yeasts, *Pichia membranifaciens* has been proven to have antimicrobial activity, and *Kluyveromyces marxianus* can be used as a single-cell protein source [65–67]. The presence of yeasts in diet may improve the protein content of the feed. In addition, high protein content of the ASW group leads to a corresponding increase in the content of some amino acids, such as cysteine and methionine, which are sulfur-containing amino acids with antimicrobial properties [68]. This may have caused the bacterial counts of the ASW group to be significantly lower than those of the ASC group ($p < 0.001$). Salting the sample before dry aging also contributes toward inhibiting bacterial growth. These results indicate that treating whey-fed pork loin with salting, dry aging, and sous vide cooking can effectively inhibit the growth of microorganisms and extend the shelf life of the meat.

4. Conclusions

Dietary supplementation with whey powder influenced the nutritional composition of the pork loin, decreasing the crude fat, total lipid, and cholesterol content and increasing the crude protein content. Whey feeding also resulted in low shear force and cooking loss. Positive effects on color stability, meat quality, and sensory evaluation were also observed with decreased cooking loss, hardness, and dry aging period when preparing the pork loin, thereby increasing the tenderness and juiciness of the meat. The combination of salting, dry aging, and sous vide cooking can improve the palatability of meat and provide protection from microbial contamination, thereby extending its shelf life. The results of this study have implications for improving pig diets, pork processing, and satisfying the requirement of consumers for a healthy diet. Additional studies on different pork cuts and novel aging methods for processing are needed to ensure high pork quality and consumer benefits.

Data Availability

The research article data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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