

## Effect of Dietary Processed Sulfur Supplementation on Texture Quality, Color and Mineral Status of Dry-cured Ham

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### Abstract

This study was performed to investigate the chemical composition, mineral status, oxidative stability, and texture attributes of dry-cured ham from pigs fed processed sulfur (S, 1 g/kg feed), and from those fed a basal diet (CON), during the period from weaning to slaughter (174 d). Total collagen content and soluble collagen of the S group was significantly higher than that of the control group ( $p < 0.05$ ). The pH of the S group was significantly higher than that of the control group, whereas the S group had a lower expressible drip compared to the control group. The S group also showed the lower lightness compared to the control group ( $p < 0.05$ ). In regard to the mineral status, the S group had significantly lower  $Fe^{2+}$  and  $Ca^{2+}$  content than the control group ( $p < 0.05$ ), whereas the proteolysis index of the S group was significantly increased compared to the control group ( $p < 0.05$ ). The feeding of processed sulfur to pigs led to increased oxidative stability, related to lipids and pigments, in the dry-cured ham ( $p < 0.05$ ). Compared to the dry-cured ham from the control group, that from the S group exhibited lower springiness and gumminess; these results suggest that feeding processed sulfur to pigs can improve the quality of the texture and enhance the oxidative stability of dry-cured ham.

**Keywords:** sulfur-fed pigs, dry cured ham, texture, meat quality, antioxidant

Received April 14, 2015; Revised July 15, 2015; Accepted July 15, 2015

### Introduction

Various feed ingredients have been utilized in the animal industry for different functional effects, such as the improvement of meat quality and oxidative stability (Moran *et al.*, 2012; Overland *et al.*, 2011; Rossi *et al.*, 2013). In particular, the feeding of sulfur to animals has been researched by many scientists, in order to establish an understanding of sulfur metabolism (Cho *et al.*, 2005; Drewnoski *et al.*, 2014; Jang *et al.*, 2006). Sulfur shows some beneficial effects in the body; for example, derivatives from organosulfur compounds stimulate apoptosis and reduce lipid accumulation (Brosnan and Brosnan, 2006; Jacob *et al.*, 2003; Lee *et al.* 2011). Kim *et al.* (2015a) reported that oxidative stability and the concentration of free amino acids in raw meat from processed sulfur-fed pigs increased. Moreover, Song *et al.* (2013) found that antioxidants involving the sulfur atom, such as sulfur containing amino acids and glutathione, increased

in pigs having a diet high in sulfur content. Recently, some scientists have attached attention to the effects of dietary sulfur on the mineral status, meat quality and antioxidant effect in animals (Drewnoski *et al.*, 2014; Kim *et al.*, 2014a; Lee *et al.*, 2009).

Dry-cured products, which are representative of the traditional meat products in Europe, are considered to be high-priced, and require a long drying and ripening process. The quality of dry-cured meat products is different, according to the conditions in which the meat was processed (including temperature, humidity and the drying-ripening period), and the level of salt in the product (Andres *et al.*, 2004; Arnau *et al.*, 2003). During the drying and ripening process, the taste of dry-cured products is directly influenced by the protease and lipase activities (Toldra and Flores, 1998). Moreover, Ventanas *et al.* (2007) suggested that the chemical components and sensory characteristics of dry-cured products are determined by the feeding strategy. Nishimura (2010) proved that the meat texture is affected by various factors, such as: the intramuscular connective tissue composition, intramuscular fat, animal growth and ageing period.

Iberian ham is recognized as a typical dry-cured meat product, and is obtained from pigs that are fed acorns.

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Because these pigs are fed acorns, Iberian hams have a high ratio of monounsaturated fatty acids and improved sensory characteristics (Tejerina *et al.*, 2011; Ventaans, 2007). A similar result was reported by Kim *et al.* (2014a), in which dry-cured ham from pigs fed 0.1% processed sulfur demonstrated an improvement of sensory characteristics compared to those being fed the basal diet.

This study was conducted to assess the effects of processed sulfur on texture quality, and the relationship between proximate compositions, the pH, the color, the proteolysis index, the mineral status and the degree of lipid oxidation in dry-cured ham.

## Materials and Methods

### Animals and experiment

A total of 60 three-way crossbred pigs (Landrace, Duroc and Berkshire) of average live weight  $8.51 \pm 1.12$  kg were assigned to two dietary treatments: the basal diet (CON) and a diet supplemented with processed sulfur (1 g/kg feed), so that each group had three replicates, with 10 pigs per pen for 174 d (the pen was provided as the experimental unit in the analyses). The dose of processed sulfur in the feed was based on the result of a previous study (Kim *et al.*, 2014a). All experimental procedures were conducted following the guidelines of the animal policy of the Konkuk University Committee (Korea).

All pigs were fed the basal diet, from weaning to slaughter, by self-feeding from a circular feeding machine. The processed sulfur was added into the basal diet (Dongaone, Korea); the processed sulfur was purchased from Jungmin (Jungmin Co., Ltd, Korea). The chemical composition of the diets was analyzed using the AOAC methods (1995), and the composition of the diet is shown in Table 1. The processed sulfur used in the S diet was prepared as a powder and mixed with the basal diet. The experimental diets were designed to fulfill the nutrient requirements for all breeding phases (NRC, 1998), and were given to the pigs *ad libitum*. The processed sulfur used in this study contained 97.9% elemental sulfur, according to the Korean Feed Ingredients Association. The pigs were slaughtered at an average live weight  $120.9 \pm 9$  kg for each treatment. After chilling for 24 h, all hams obtained from the pigs (for each treatment) were transported by a cooling conditioned vehicle from the slaughterhouse into a laboratory at Konkuk University.

### Preparation of dry-cured ham and sampling

The hams were trimmed of excess fat and skin immedi-

**Table 1. Formula and chemical composition of experimental diets in growing-finishing pigs**

Items	Basal diet
Ingredients (%)	
Corn	40.92
Wheat	28
Rice bran	2
Soybean meal	17.1
Rapeseed meal	3
Corn germ meal	2.5
Animal fat and oil	2.07
Molasses	2
Limestone	0.99
Calcium phosphate	0.19
Salt	0.3
Lysine 25% (liquid)	0.44
Threonine 98% (powder)	0.04
Choline chloride 50% (powder)	0.1
Vitamin/Mineral/etc <sup>2)</sup>	0.35
Processed sulfur	
Total	100
Chemical composition (%)	
Crude protein	16.0
Crude fat	4.48
Crude fiber	4.03
Crude ash	3.99
Calcium	0.65
Phosphorus	0.39

<sup>1)</sup>CON, non-treated dietary fed groups; S, 0.3% processed sulfur fed groups.

<sup>2)</sup>Vitamin/Mineral/etc, Supplied per kilogram of diet: 45 mg Fe, 0.25 mg Co, 50 mg Cu, 15 mg Mn, 25 mg Zn, 0.35 mg I, 0.13 mg Se, 16,000 IU vitamin A, 3,000 IU vitamin D3, 40 IU vitamin E, 5.0 mg vitamin K3, 5.0 mg vitamin B1, 20 mg vitamin B2, 4 mg vitamin B6, 0.08 mg vitamin B12, 40 mg pantothenic acid, 75 mg niacin, 0.15 mg biotin, 0.65 mg folic acid, 12 mg antioxidant.

ately after transport. Salt (5% Meat Weight Basis) was rubbed on the surface of the hams. They were then placed for 3 mon in a refrigerated room to maintain a low temperature of 4°C and a relative humidity of 70-80% during the salting phase. The salted hams were soaked in tepid water to remove the salt at 3 mon post-salting. The hams were hung, at 12°C difference from the initial temperature after washing; the condition of environment was determined by a temperature increase of up to 19°C (1°C per week), and an RH of 40-60%, for 6 mon. In this study, the *biceps femoris* muscles were collected, to conduct all experiments on all dry-cured hams after 12 mon.

### Proximate composition, collagen, pH, water activity ( $a_w$ ), expressible drip and color

The dry-cured ham of the control and the sulfur-fed groups were analyzed for their proximate compositions

(moisture, fat, protein and ash), according to Association of Analytical Chemists methods (AOAC, 1995).

The collagen content was analyzed using the method employed by Silva *et al.* (1999). A 4 g sample was placed in a flask with 30 mL of 6 N HCl and then hydrolysis was conducted on the sample for 16 h at 110°C in a drying oven. The hydrolyzed sample was adjusted to 500 mL volume in a flask. An aliquot of the diluted sample was reacted with 1 mL of oxidant solution for 20 min. The oxidative sample was mixed with 1 mL of color reagent, at 60°C for 15 min in a water bath, and then cooled to room temperature; the absorbance was measured at 550 nm in wavelength, to determine the amount of hydroxyproline.

The collagen solubility was measured according to the method employed by Liu *et al.* (1999), with a slight modification. 4 g of the sample was homogenized, with 12 mL of ¼ Ringer's Solution (Oxoid, Italy). Then, the homogenate was reacted in a water bath at 75°C, for 70 min. The reacted homogenate was centrifuged for 20 min with 3000 g at 4°C. The precipitated pellet was dried in a drying oven, and the collagen content of the sediment was determined, as described at upper. The collagen solubility of the meat was expressed as a percentage of the soluble collagen from the total collagen.

The pH of the samples was measured using a pH meter (pH 900, Precisa Co, UK). The water activity was determined in dry-cured ham using a water activity measuring device (Aqua Lab CX-2, Decagon Device Inc., Germany). The expressible drip was measured, according to the method employed by Schilling *et al.* (2003), with a slight modification. The samples were placed between two Whatman No.1 filter papers, and pressed with 9.9 kg/cm<sup>2</sup> force for 30 min (IF 32B-S50, Ilshin Tech. Co. Ltd., Korea). The pressed sample was weighed after being removed from the paper. The expressible drip was then calculated as a percentage:

$$[(\text{initial weight} - \text{final weight}) / \text{initial weight}] \times 100$$

The sample color was measured using a Handy colorimeter (NR-300, Nippon Denshoku, Japan); the machine was calibrated with a white plate (CIE L\* = +94.48, a\* = -0.67, b\* = +3.31). The values of CIE L\*(lightness), CIE a\*(redness), and CIE b\*(yellowness) were recorded during storage.

#### Proteolysis index

The total nitrogen (TN) content was determined using the Kjeldahl method, in a Kjeldahl Foss automatic system, and expressed as g/100g of dry sample matter. The

non-protein nitrogen (NPN) was measured according to the method employed by Careri *et al.* (1993). 10 g of minced sample was homogenized with 90 mL of distilled water; the homogenate was then centrifuged at 8500 g, for 15 min, at 5°C. An aliquot (10 mL) of the separated supernatant was mixed with 10 mL of 5% trichloroacetic acid, and allowed to react overnight at 4°C. The reacted solution was centrifuged at 8500 g, for 10 min at 5°C, and filtered through Whatman No. 4 filter paper. The NPN was determined from 3 mL of the filtrate using the Kjeldahl method, in a Kjeldahl Foss automatic system, and expressed as mg/100g of dry sample matter. The proteolysis index (PI) was calculated as the percentage ratio between the NPN and the TN (Careri *et al.*, 1993).

#### 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical scavenging activity

The scavenging ability of the meat toward the free radical DPPH was measured following the method employed by Overland *et al.* (2011). 5 g samples were homogenized with 20 mL of methanol using a Bag mixer 400 (Interscience Co, St. Nom la Bretèche, France) and then sonicated for 10 min (Branson 321, USA). After sonication, the sample was separated by centrifugation for 10 min at 10,000 g (4°C). The separated supernatant was diluted in a 50 mL volumetric flask. An aliquot (0.1 mL) of the extract in methanol was reacted with 2.4 mL of methanolic DPPH solution (25 mg/L) in a dark room (25°C) for 2 h. The absorbance was measured at 515 nm, using a spectrophotometer (Optizen 2120UV, Mecasys, Korea).

#### Mineral status

The concentration of calcium (Ca) and iron (Fe) trace mineral were determined by coupled plasma spectrometry (ICP; VGElemental PlasmaQuad SOption).

#### Lipid oxidation

The lipid oxidation of the dry-cured ham was determined, in triplicate, according to a modified 2-thiobarbituric acid (TBA) method from Witte *et al.* (1970). A 10 g sample was blended with 50 mL of 10% trichloroacetic acid and 50 mL of distilled water, and then homogenized for 1 min. The mix was filtrated using Whatman No. 1 filter paper. 5 mL of supernatant was mixed with 5 mL of 2-thiobarbituric acid, and then boiled in a water bath at 90°C for 10 min. The absorbance of the supernatant was measured at 532 nm using a spectrophotometer (Optizen 2120UV; Mecasys, Korea). The results were expressed as malondialdehyde (MDA) mg/ meat kg. The value of the

TBARS was calculated from a standard curve of MDA, by the acidification of 1,1,3,3-tetraethoxypropane (TEP).

### Metmyoglobin

For the pigment oxidation stability evaluation, the samples were placed in a 45°C dry oven for 24 h. A 4 g sample was homogenized with 20 mL of 0.04 M phosphate buffer (pH 6.8) using a homogenizer (AM-7, Nihonseiki Kaisha, Japan), at 13,000 rpm for 10 s. The mixed sample was stored at 4°C for 1 h, and centrifuged at 5,000 g for 30 min at 5°C. The supernatant was filtered through Whatman No.1 paper, and the absorbance was measured by spectrophotometry (Optizen 2120 UV, Mecasys, Korea). The metmyoglobin (%) of the dry cured ham was acquired by the following formula (Krzywicki, 1979):

$$\text{Metmyoglobin (\%)} = \{1.395 - (A572 - A700) / (A525 - A700)\} \times 100$$

where A525 = absorbance at 525 nm, A572 = absorbance at 572 nm and A700 = absorbance at 700 nm.

### Shear Force

The Warner-Braztler test was conducted on the dry-cured ham, using the TA-XT2i texture analyzer (Stable Micro Systems, UK). The samples were prepared at approximately 1 × 1 × 2.5 cm (height × width × length), which was fixed in the muscle fiber direction. The shear force test was set up according to the method employed by Bermudez *et al* (2014); a shear blade with a triangular slot cutting edge (1 mm thickness) at a crosshead speed of 3.33 mm/s.

### Texture profile analysis

A Texture Analyzer CT3 (Brookfield Engineering Laboratories, Inc., USA) was used to measure the texture profiles (hardness, springiness, cohesiveness, chewiness and gumminess), at room temperature, using a 25 kg load cell. The samples were kept for an hour at room temperature before conducting the texture analyses. A 6 mm diameter stainless plunger was used in the TPA tests. Duplicate cubes of 2.54 × 2.54 × 1.27 cm (length × width × height), which were cut out lengthwise from the fiber direction, were analyzed. The assay was done with the following conditions: The force-time curves were recorded at a crosshead speed of 1.0 mm/s and the trigger force was 0.98 N. The samples were compressed twice, to 40% of their original height, with an interval of 2 s between them. The values for hardness (kg), springiness (mm), cohesive-

ness, gumminess (kg) and chewiness (mJ) were calculated by the results of the assay.

### Statistical analysis

Statistical analyses of the data were conducted using SPSS 18.0. Data on the proximate compositions, the pH, the water activity, the expressible drip, the color (lightness, redness and yellowness), the metmyoglobin, the TBARS value, the DPPH, the minerals, the proteolysis index and the texture parameters, were analyzed with a one-way analysis of variance (ANOVA), in which the diet was fixed as the main factor. A significant difference between the CON and S groups was analyzed using an independent *t*-test. All statistical tests of means were performed for a level of significance ( $p < 0.05$ ). Correlations between all parameters were determined through correlation analyses, using the Pearson's linear correlation coefficient with SPSS 18.0.

## Results and Discussion

### Effects of processed sulfur on physicochemical properties, pH, expressible drip and color of dry-cured ham

The data on the physicochemical properties, the pH, the expressible drip and the color of dry-cured ham is shown in Table 2. The moisture, crude protein and ash content between the CON and S groups did not show significant

**Table 2. Physical characteristics and color of dry-cured ham from pig fed by diets supplemented with the processed sulfur**

	CON	S	SEM	<i>p</i> -value
Moisture (%)	54.66	53.89	0.37	0.420
Crude fat (%)	3.09 <sup>a</sup>	1.50 <sup>b</sup>	0.05	<0.001
Crude protein (%)	36.35	33.83	0.85	0.122
Ash (%)	9.07	8.50	0.20	0.191
Total Collagen (g/kg)	16.08 <sup>b</sup>	19.45 <sup>a</sup>	0.72	0.043
Collagen solubility (% of total collagen)	9.54 <sup>b</sup>	12.67 <sup>a</sup>	0.50	0.035
Expressible drip (%)	35.69 <sup>a</sup>	31.61 <sup>b</sup>	0.92	0.020
pH	6.13 <sup>b</sup>	6.45 <sup>a</sup>	0.05	0.015
<i>a<sub>w</sub></i>	0.902 <sup>b</sup>	0.912 <sup>a</sup>	0.001	0.017
Total nitrogen	5.82	5.41	0.14	0.152
NPN (%) <sup>1)</sup>	0.39 <sup>b</sup>	0.52 <sup>a</sup>	0.02	0.005
Proteolysis index (%)	6.72 <sup>b</sup>	9.67 <sup>a</sup>	0.25	0.002
Color				
Lightness ( <i>L</i> <sup>*</sup> )	43.85 <sup>a</sup>	40.16 <sup>b</sup>	0.94	0.018
Redness ( <i>a</i> <sup>*</sup> )	17.46	17.00	0.51	0.526
Yellowness ( <i>b</i> <sup>*</sup> )	14.84	15.13	0.52	0.725

SEM, standard error of the mean (n=5); CON, control group; S, 0.1% processed sulfur fed pigs.

differences ( $p>0.05$ ), whereas the fat content of S group was significantly lower than that of CON group ( $p<0.05$ ). A reduction in the fat content in the meat of sulfur-fed pigs was reported by Kim *et al.* (2015a). It has been confirmed that the inhibition of lipid accumulation was promoted through the inactivation of adipogenic genes by the intake sulfur compounds (Lee *et al.*, 2011). The collagen content and collagen solubility of the S group were significantly higher than those of the CON ( $p<0.05$ ). Brown *et al.* (1965) reported that collagen synthesis was reduced by the limitation of dietary sulfur, due to the inhibition of fibroblast activity. Some scientists have indicated that the conversion ratio of collagen to soluble collagen increases under the absence of oxidative stress, and that this may improve meat texture (Archile-Contreras and Purslow, 2011; Archile-Contreras *et al.*, 2011). A negative correlation was proved between the lipid oxidation and collagen solubility ( $r=-0.80$ ,  $p<0.01$ ). Also, the collagen solubility was increased in the meat due to the degradation of the protein throughout the ripening process (Cordoba *et al.*, 1994).

The pH of the S group was found to be significantly higher than that of the CON ( $p<0.05$ ). According to Armou *et al.* (1995), the increasing pH of the dry-cured ham occurred as a result of the proteolysis during the aging period. This phenomenon was occurred by the accumulation of ammonia formation generated from protease activities (Virgili *et al.*, 2007). Besides, the expressible drip of the S group was significantly lower than that of the CON group ( $p<0.05$ ). These results might be because the pH value of the meat is considered to be an important factor, in relation to the water holding capacity of meat, because of the establishment of a strong repulsive force to activate the water binding energy (Offer and Knight, 1988).

There was a no significant difference between both groups in regard to the total nitrogen content ( $p>0.05$ ). The NPN of the S group was significantly higher than that of CON ( $p<0.05$ ), and the proteolysis index of the S group was also significantly higher than that of CON ( $p<0.05$ ). Virgili *et al.* (2007) pronounced that NPN has positive relation with free amino acids during the ageing of dry cured ham. The proteolysis index is affected by various protease activities during the ripening period. The protease activities of dry-cured ham are influenced by a number of factors, such as additives, pH, temperature and humidity conditions during the ripening period. Pogge *et al.* (2013) suggested that the protease activities of meat could be increased though the inhibition of lipid oxidation. The higher free amino acids content and oxidative

stability of dry cured loin from processed sulfur fed pigs were reported compared with normal pigs by Kim *et al.* (2015b).

The lightness ( $L^*$ ) of the dry-cured ham from the sulfur-fed pigs was significantly lower than that of the CON group ( $p<0.05$ ). However, there were no significant differences between the treatments in both the redness and yellowness ( $p>0.05$ ). Wilkins *et al.* reported that the pH has negative correlations with lightness and yellowness, and a negative correlation between the pH and the lightness was found in this study ( $r=-0.72$ ,  $p<0.01$ ).

### Mineral status and proteolysis index of dry-cured ham

Table 3 shows the mineral status and proteolysis index of the dry-cured ham. Both the calcium and iron content of the S group were significantly lower than that of the CON group ( $p<0.001$ ). The reduction of iron inhibited lipid oxidation due to the suppression of reacting with free radical in meat (Tang *et al.*, 2000). Moreover, discoloration effect might be occurred because of binding with iron and myoglobin (Mitsumoto *et al.*, 2005). Ferrous iron is converted to insoluble ferrous sulfide by a reaction with hydrogen sulfide, which is generated from sulfur compounds; this reaction retards the absorption of ferric iron in the intestine (Drewnoski *et al.*, 2013; Ebrahimi *et al.*, 2002; Magee *et al.*, 2000).

A reduction in the  $Ca^{2+}$  content of meat from pigs fed methyl sulfonyl methane (MSM) was reported by Lee *et al.* (2009). Due to effect of the sulfur supplementation in the diet of the pigs, the increase in methionine and cystine promoted the excretion of calcium from the body (Song *et al.*, 2013; Wang and Zhao, 1988). The formation of IP3 R, which is used as a meat quality biomarker, was stimulated by the release of  $Ca^{2+}$ , and an increase of IP3 R is found in low quality grade meat (Kim *et al.*, 2008).

### Antioxidant potential and oxidative stability of dry-cured ham

The DPPH free radical scavenging activity (%) and oxidative stability of dry-cured ham were shown in Table 4. The DPPH free radical scavenging activity of the S group

**Table 3. Mineral status of dry-cured ham from pig fed by diets supplemented with the processed sulfur**

	CON	S	SEM	<i>p</i> -value
Ca, mg/kg	258.56 <sup>a</sup>	144.31 <sup>b</sup>	0.16	<0.001
Fe, mg/kg	7.97 <sup>a</sup>	4.12 <sup>b</sup>	0.06	<0.001

SEM, standard error of the mean (n=5); CON, control group; S, 0.1% processed sulfur fed pigs; <sup>1</sup>NPN, non-protein nitrogen.

**Table 4. DPPH free radical scavenging activity, oxidative stability of dry-cured ham from pig fed by diets supplemented with the processed sulfur**

	CON	S	SEM	<i>p</i> -value
DPPH free radical scavenging activity (%)	16.05 <sup>b</sup>	20.97 <sup>a</sup>	0.375	0.003
TBARS <sup>1)</sup>	0.35 <sup>a</sup>	0.26 <sup>b</sup>	0.02	0.010
Metmyoglobin (%)	78.36 <sup>a</sup>	73.94 <sup>b</sup>	0.35	<0.001

SEM, standard error of the mean (n=5); CON, control group; S, 0.1% processed sulfur fed pigs.

<sup>1)</sup>TBARS units, MDA mg/kg.

was significantly higher than that of the CON group ( $p < 0.01$ ). The antioxidant activities of the meat were enhanced because of the increasing protein hydrolysates, which had an ability to retard the lipid oxidation (Bougatef *et al.*, 2009). In addition, Song *et al.* (2013) determined that feeding a high sulfur content diet affected the occurrence of sulfur-containing antioxidants such as methionine, cysteine and glutathione. It is assumed that the S group is a possibility to maintain sulfur compounds of high rate, which the compounds have an excellent ability to act as efficient free radical scavengers. The TBA value (malondialdehyde mg/kg) of the S group showed a lower value than that of the CON group ( $p < 0.01$ ). There was a positive correlation between the iron content and the TBA value in this study ( $r = 0.90$ ,  $p < 0.01$ ). Tang *et al.* (2000) suggested that lipid oxidation was induced by the accumulation of iron in chicken meat. The reduction of iron in meat could enhance the oxidative stability of dry-cured ham from processed sulfur-fed pigs. Besides, methionine and cysteine are reactive with hydroperoxide, generated from lipid peroxidation, due to the reducing power of the sulfur atom; the chain reaction of lipid oxidation is blocked by the formation of sulfoxide (Slump and Schreuder, 1973). Kim *et al.* (2014a) and Kim *et al.* (2014b) documented a lower TBA value of meat products from sulfur-fed pigs than in meat from basal diet-fed pigs.

The metmyoglobin (MetMb) of the S group was converted by a lower level when compared with the CON group ( $p < 0.001$ ). The MetMb content is considered an important parameter of pigment oxidation, and several factors could manipulate pigment oxidation, such as preservation treatments, cooking process, fat content, pH and package methods (King and Whyte, 2006). Furthermore, the primary and secondary products that are decomposed from lipid oxidation stimulate pigment oxidation; pigment oxidation has a positive correlation with lipid oxidation (Faustman *et al.*, 2010). The positive correlation between the TBARS and the metmyoglobin content was determined ( $r = 0.88$ ,  $p < 0.01$ ). On the other hand, the metmyoglobin concentration in beef with sulfur supplementation was lower than that of beef with Vitamin E sup-

plementation, although the degree of lipid oxidation in beef with sulfur supplementation showed an increase compared to beef with Vitamin E supplementation (Lee *et al.*, 2008). In addition, studies by Warriss (2000) showed that the oxidation of the myoglobin to MetMb tends to be promoted at a lower pH. These results may have occurred, since the decrease in iron concentration affects the meat color.

#### Texture profile analysis (TPA)

The TPA parameters of dry-cured ham from the non-processed sulfur-fed pigs, and processed sulfur-fed pigs, are shown in Table 5. The dry-cured ham from pigs treated with processed sulfur maintained some tendency toward a lower shear force than the control ( $p < 0.1$ ). The shear force has a negative correlation with the proteolysis index and the collagen solubility ( $r = -0.83$  and  $r = -0.95$ ,  $p < 0.01$ ). Likewise, gumminess and cohesiveness of dry-cured ham from processed sulfur-fed pigs showed a tendency to be lower compared to the control group ( $p < 0.1$ ). According to Lorenzo *et al.* (2014), the water activity had negative correlations with both the gumminess and the cohesiveness. In this study, the water activity and the gumminess had a negative correlation ( $r = -0.66$ ,  $p < 0.05$ ). The springiness of dry-cured ham from processed sulfur-fed pigs was significantly lower than that of the CON group ( $p < 0.05$ ). No significant differences regarding the hardness and chewiness of dry-cured ham, due to the dietary supplementation of processed sulfur, were observed in this study ( $p >$

**Table 5. The textural attributes of dry-cured ham from pig fed by diets supplemented with the processed sulfur (S) supplemented diets from weaning to fattening phase**

Parameters	CON	S	SEM	<i>p</i> -value
Shear force (kg)	5.25	4.51	0.18	0.07
Hardness (kg)	8.41	7.62	1.02	0.62
Springiness (mm)	5.70	4.85	0.18	0.03
Cohesiveness	0.43	0.39	0.01	0.10
Gumminess (kg)	3.19	1.84	0.36	0.09
Chewiness (mJ)	164.47	155.17	6.87	0.39

SEM, standard error of the mean (n=5); CON, control group; S, 0.1% processed sulfur fed pigs.

**Table 6. Pearson correlations among metmyoglobin (Metmb), TBARS, color (lightness, redness and yellowness), collagen solubility (CS), proteolysis index (PI), minerals and texture profile**

	TBARS	L*	a*	b*	CS	PI	HS	CHS	SPG	GM	CWN	SF	Iron	Calcium
Metmb	0.88**	-0.63**	0.023	-0.31	-0.84**	-0.92**	0.52	0.41	0.35	0.74**	-0.89	0.77**	0.95**	0.95**
TBARS	1	-0.57*	0.08	-0.11	-0.80**	-0.89**	0.48	0.31	0.41	0.63	0.12	0.76**	0.92**	0.93**
L*		1	0.06	0.66**	0.33	-0.59	-0.55	-0.24	-0.17	-0.70*	0.81	-0.33	-0.53*	-0.54*
a*			1	0.37	-0.13	-0.22	0.03	0.12	0.28	0.05	0.37	-0.22	0.16	0.17
b*				1	0.02	0.11	-0.19	-0.20	0.35	-0.35	0.99*	-0.12	-0.06	-0.07
CS					1	0.88**	-0.52	-0.08	-0.60*	-0.54	-0.12	-0.95**	-0.90**	-0.90**
PI						1	-0.37	-0.32	-0.43	-0.52	0.12	-0.83**	-0.97**	-0.97**
HS							1	-0.33	0.67*	0.87**	-0.37	0.44	0.50	0.50
CHS								1	-0.56	0.17	-0.82	0.13	0.26	0.26
SPG									1	0.36	0.96	0.58	0.51	0.51
GM										1	-0.93	0.48	0.62*	0.62*
CWN											1	0.12	0.12	0.12
SF												1	0.80**	0.80**

Only significant correlations are shown. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .

0.05). According to Bailey and Light (1989), muscles with high collagen content showed a lower compressive-force value than that of other muscles with low collagen content. However, no correlations between the collagen content and the texture parameters were shown in this study.

#### Relationship between metmyoglobin (Metmb), TBARS, color (lightness, redness and yellowness), collagen solubility (CS), proteolysis index (PI) and texture profile

Pearson's correlations among the variables studied are expressed in Table 6. The iron content has highly positive correlations with the Metmb and the TBARS ( $r = 0.95$ ,  $p < 0.01$ ;  $r = 0.92$ ,  $p < 0.01$ ). Meanwhile, the lipid oxidation has negative correlations with both the collagen solubility and the proteolysis index ( $r = -0.80$ ,  $p < 0.01$ ;  $r = -0.90$ ,  $p < 0.01$ ). In addition, a positive correlation between the collagen solubility and the proteolysis index was shown ( $r = 0.88$ ,  $p < 0.01$ ), and both the CS and the PI have negative correlations with shear force ( $r = -0.95$ ,  $p < 0.01$ ;  $r = -0.83$ ,  $p < 0.01$ ).

#### Conclusion

The results of this study suggest that supplementation with processed sulfur increases the antioxidant ability, the pH, the expressible drip, the lightness and the texture attributes in dry-cured ham. We also found that the collagen solubility was increased in dry-cured ham from pigs supplemented with processed sulfur. Additionally, the lower shear force and higher proteolysis index of dry cured ham from processed sulfur-fed pigs were proven, compared to the basal diet-fed pigs. In conclusion, the feeding of 0.1% processed sulfur to pigs, used for the production of high

dry-cured ham quality and to reduce the ripening period during manufacturing.

#### Acknowledgements

This research was supported by the Technology Commercialization Support Program, iPET (Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries), Ministry of Agriculture, Food and Rural Affairs, the Republic of Korea.

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