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Color development, physiochemical properties, and microbiological safety of pork jerky processed with atmospheric pressure plasma

Hae In Yong[a], Sang Hui Lee[a], So Yeon Kim[a], Sanghoo Park[b], Jooyoung Park[b], Wonho Choe[b], Cheorun Jo[a,c,*]

[a] Department of Agricultural Biotechnology, Center for Food and Bioconvergence, and Research Institute of Agriculture and Life Science, Seoul National University, Seoul 08826, South Korea
[b] Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea
[c] Institute of Green Bio Science and Technology, Seoul National University, Pyeongchang 25354, Republic of Korea

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ABSTRACT

We investigated the applicability of atmospheric pressure plasma (APP) as an alternative to sodium nitrite in pork jerky manufacturing. Pork slices were marinated in brine with no sodium nitrite at 4 °C for 16 h and treated by APP for 0, 20, 40, and 60 min, respectively. The sample marinated in the brine with sodium nitrite (100 ppm) was also prepared. Then, all samples were dried. As APP treatment time increased, the a^* value (redness), nitrosoheme pigment content, and residual nitrite content increased, while lipid oxidation decreased (all $P < 0.05$). Similar quality properties, particularly color, were observed in jerky applied by APP for 40 min compared to jerky made with sodium nitrite. After inoculation of marinated pork with *Staphylococcus aureus* or *Bacillus cereus*, the amounts of both pathogens in jerky applied by APP for 40 and 60 min were significantly lower than in jerky made with sodium nitrite. Consequently, APP can be applied for manufacturing potentially safer pork jerky without added sodium nitrite.

Industrial relevance: The global interest in sodium nitrite substitute for meat products manufacturing has considerably grown for years because consumer's demand of foods labeled “natural” and “chemical-free” has been increasing. In general, APP is recognized as a novel non-thermal food processing technology that uses energetic, reactive species to inactivate microbes on various foods. Recently, meat curing system involving direct APP treatment was proposed. The present study tried to apply APP to manufacturing pork jerky without using sodium nitrite. As a result, similar quality properties, particularly color, were observed in jerky applied by APP compared to jerky made with sodium nitrite. Application of APP also improved the microbiological safety of pork jerky. Therefore, APP can be applied for manufacturing potentially safer pork jerky by inactivation of heat-resistant pathogens without added sodium nitrite.

1. Introduction

The salt curing of meat is a preservation technology practiced since ancient times. In the 19th century, certain salts (saltpeter, KNO_3) were preferred for the curing process, because their preserving capacities for meat products were recognized to be better than other salts. Later, people realized that the nitrate (NO_3^-) in saltpeter is converted by naturally occurring bacteria to nitrite (NO_2^-), which plays a major role in curing (Akköse, Ünal, Yalınkılıç, Kaban, & Kaya, 2017; Honikel, 2008). Nitrite prevents lipid oxidation, controls the growth of *Clostridium botulinum*, and produces a red color and unique flavor in meat products. For these reasons, synthetic nitrites, including potassium and sodium nitrites, have been used in meat curing for decades (Alahakoon, Jayasena, Ramachandra, & Jo, 2015; Parthasarathy & Bryan, 2012; Pegg, Shahidi, & Fox, 1997).

Meanwhile, today's food industry is confronted with changing market trends, as consumption of foods labeled “natural” and “chemical-free” has been increasing. In response to consumer demand, cured meat producers have begun to use vegetable powders containing high concentrations of nitrates an alternative to synthetic nitrite, and refer to these products as “naturally cured” (Sebranek, Jackson-Davis, Myers, & Lavieri, 2012). However, using vegetable powder is expensive and time-consuming because it requires incubation with a starter culture to convert nitrate to nitrite. The amount of vegetable powder that

* Corresponding author at: Department of Agricultural Biotechnology, Center for Food and Bioconvergence, and Research Institute of Agriculture and Life Science, Seoul National University, Seoul 08826, South Korea.
E-mail address: cheorun@snu.ac.kr (C. Jo).

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can be added to meat products is also limited due to its undesirable flavor (Alahakoon et al., 2015; Jung et al., 2015). Thus, the search for an alternative to nitrite for meat curing continues.

Plasma is an ionized gas made of reactive neutral species, with sufficient energy to break covalent bonds and initiate chemical reactions (Niemira & Gutsol, 2011). Plasma generated under atmospheric pressure is called atmospheric pressure plasma (APP), and this technology has attracted attention as an innovative method of non-thermal sterilization (Misra & Jo, 2017; Yong et al., 2015). Recently, it was reported that APP-treated water contains plenty of reactive species, such as nitrite and nitrate (Machala et al., 2013; Oehmigen et al., 2010). Based on this, our previous studies suggested the possibility of using APP-treated water as a new nitrite source in curing processes, as emulsion-type sausages cured with APP-treated water showed similar color, lipid oxidation, and sensory properties to sausage cured with commercial sodium nitrite (Jung et al., 2015; Lee, Lee, et al., 2017). No mutagenicity and immune toxicity were detected in sausage cured using APP-treated water (Kim et al., 2016). However, APP-treated water itself could be considered an additive.

Subsequently, a meat curing system involving direct APP treatment was suggested. When a meat batter composed of pork, water, and sodium chloride was treated with APP during the mixing process, the red color of cured meat developed in the batter without any negative quality changes (Jung et al., 2017). Meanwhile, the number of total aerobic bacteria in the meat batter was not influenced by APP treatment, even though APP is widely recognized as a non-thermal sterilization technology (Jung et al., 2017).

Our hypothesis is that the use of APP in processed meat manufacturing can simultaneously inactivate pathogens and cure the meat. Through this system, potentially safer but added sodium nitrite-free meat products could be produced. Jerky is a typical meat product that is popular in many countries due to its taste, nutrition, and portability (Yong, Lee, et al., 2017). In the present study, pork jerky was made using APP without the addition of synthetic nitrite sources. The cured color development, physiochemical properties, and microbiological safety were compared between pork jerky made with APP and sodium nitrite. The possible reasons behind the cured color development in the APP pork jerky were also investigated.

2. Materials and methods

2.1. Production of pork jerky

2.1.1. Experimental design and production process

Raw pork (*Musculus biceps femoris*), sliced to 7-mm thickness, was purchased from a local meat market and randomly divided into two groups. In the first group, the pork slices were cut to 10 × 10 cm^2 and used to analyze the physiochemical properties of jerky made with APP and sodium nitrite. Pork slices in the second group were cut to 3 × 3.5 cm^2 and used in pathogen inoculation tests to compare the bactericidal effects of the treatments. Fig. 1 shows the experimental design and process of pork jerky production.

To produce the jerky, two different brines were prepared with the following compositions (w/w, based on raw meat weight): i) Sodium nitrite-free brine: 20% water, 0.15% salt, and 0.03% ascorbic acid; ii) Sodium nitrite-added brine: 20% water, 0.15% salt, 0.03% ascorbic acid, and 0.01% sodium nitrite. Pork slices were marinated in each brine at 4 °C for 16 h, removed from the marinades, and placed on dielectric dishes. Pork marinated in sodium nitrite-free brine was exposed to APP for 0, 20, 40, and 60 min. Pork marinated in nitrite brine was kept at room temperature without any other processing during the APP treatment (2 h). Then, all samples including APP- and sodium nitrite-cured were placed in a drying oven (DS-510L, Daewonsci Inc., Bucheon, Korea), dried at 75 °C for 150 min, 65 °C for 90 min, and 55 °C for 90 min, and cooled, resulting in APP- and sodium nitrite-cured pork jerkies. Among the treatments, APP treatment for 0 min is a negative control while a sodium nitrite treatment is a positive control.

2.1.2. APP treatment

The APP system used in the present study consisted of an array of four dielectric barrier discharge (DBD) sheets and a gas-tight chamber. A detailed configuration of the DBD source can found in Jung et al. (2015). As presented in Fig. 2(a), two metallic sheets with 3 × 3 mm^2 rounded square patterns were adhered on both sides of a 1 mm thick, 10 × 10 cm^2 alumina plate. One electrode was connected to the power supply, which provided a sinusoidal waveform at a frequency of 4 kHz and a peak-to-peak voltage of 3.8 kV. The other electrode was used as a ground electrode, and air surface discharge was generated at the surface of the electrodes. Plasma was produced in the ambient air without air circulation or supplementation with any particular gas. Fig. 2(b) shows an arrangement of the vertically aligned DBD array and a sample inside the gas-tight chamber. The distance between the sample surface and the DBD array was fixed at 1 cm throughout the experiment. The molecular spectra of NO_g, N_2, and N_2^+ were detected in emission spectrum of plasma from the same DBD system (Yong, Park, et al., 2017).

To expose both sides of the pork samples to APP, the samples were inverted halfway through APP treatment. Since each side of the samples was exposed to APP for 0, 10, 20, or 30 min, the total APP treatment times were 0, 20, 40, and 60 min, respectively.

2.2. Physicochemical properties of pork jerky

2.2.1. Color

Color measurements were performed using a colorimeter (CM-5, Konica Minolta Co., Ltd., Osaka, Japan), using Standard Illuminant D65, a 10° standard observer, and a 30 mm (diameter) measurement area. The color values were expressed as L^* (+ brightness, − darkness), a^* (+ redness, − greenness), and b^* (+ yellowness, − blueness) values. Then, chroma ($C = \sqrt{a^2 + b^2}$) were calculated from the a^* and b^* values.

2.2.2. Nitrosoheme pigment and residual nitrite content

Nitrosoheme pigment content was measured according to Hornsey (1956) and Hunt et al. (2012). The pigments in pork jerky were extracted with an acetone:distilled water (60:40, v/v) solution. The extract was filtered through a Whatman No. 4 filter paper (Whatman PLC., Maidstone, UK). The absorbance was measured at 540 nm using a spectrophotometer (X-ma 3100, Human Co. Ltd., Seoul, Korea) and was multiplied by 290 which is the conversion factor to measure a nitrosoheme pigment (ppm of hematin).

Residual nitrite in pork jerky samples was measured as described by AOAC method no. 973.31 (AOAC, 1990).

2.2.3. Lipid oxidation

Lipid oxidation was evaluated by measuring the concentration of malondialdehyde, which is a byproduct of the oxidation of polyunsaturated fatty acids (Misra & Jo, 2017), as a 2-thiobarbituric acid reactive substances (TBARS) value. The TBARS values of the pork jerkies were measured according to method by Kim, Yong, Park, Choe, and Jo (2013). Each pork jerky sample (5 g) was homogenized with 15 mL of distilled water using a homogenizer (T10 basic). The homogenate (2 mL) was transferred to a test tube and mixed with 4 mL of thiobarbituric acid (0.02 M)/trichloroacetic acid (15%) solution. Then, the test tubes were heated in a water bath at 90 °C for 30 min, cooled, and centrifuged (Continent 512R, Hanil Co., Ltd., Incheon, Korea) at 2419 × g for 10 min. The absorbance of the supernatant was measured at 532 nm using a spectrophotometer (X-ma 3100). The amount of malondialdehyde was calculated using a standard curve prepared from 1,1,3,3-tetraethoxypropane, and the TBARS value was reported as mg malondialdehyde per kg meat.

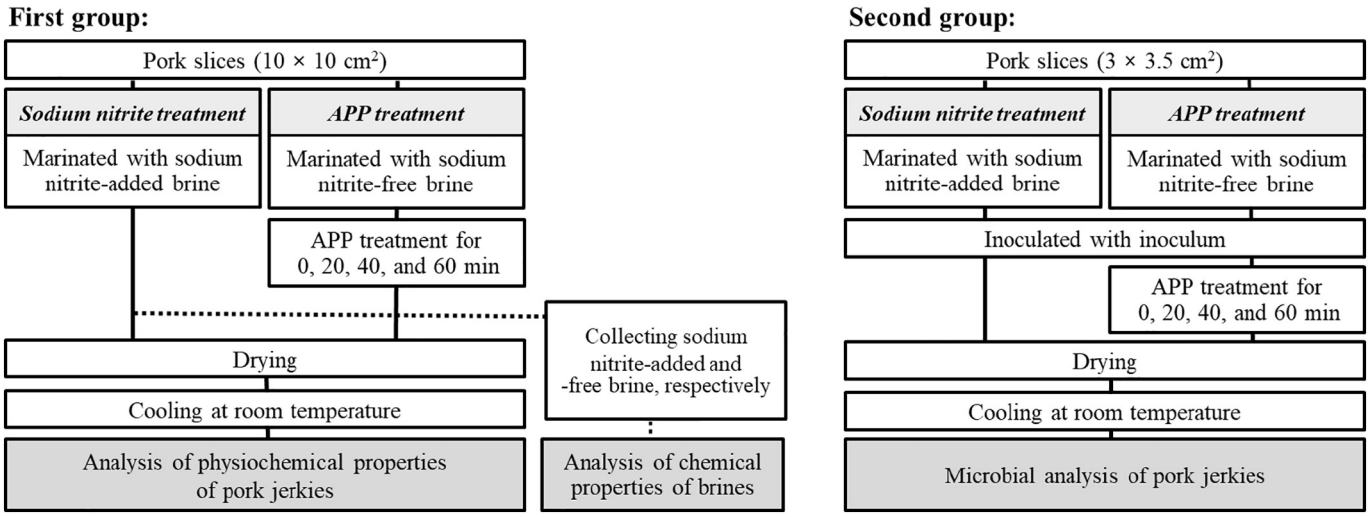

Fig. 1. Experimental design and process of pork jerky production.

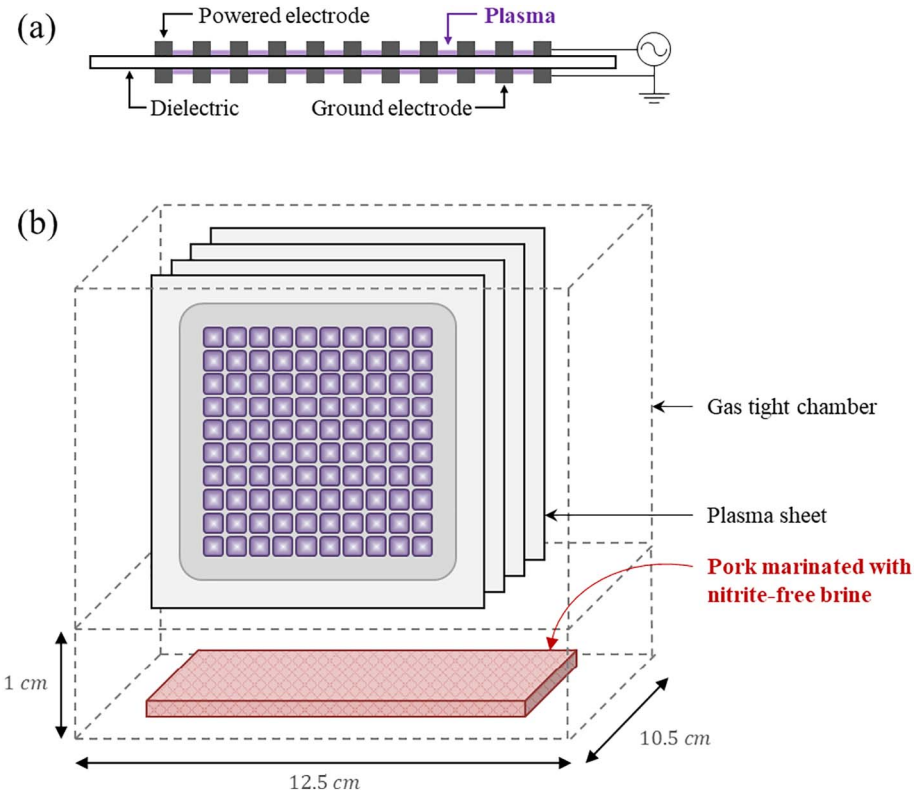

Fig. 2. (a) Detailed illustration of the dielectric barrier discharge (DBD) plasma source, and (b) schematic diagram of the full atmospheric pressure plasma (APP) treatment system.

2.2.4. Water activity (A_w) and shear force measurements

The A_w of each pork jerky sample (5 g) was measured using an Aqualab model 4TE A_w meter (Decagon Devices Inc., Pullman, WA, USA).

Pork jerky samples were cut into 10 × 30 mm^2 pieces and their shear force (N) value was measured using a Warner Bratzler blade attachment on a texture analyzer (AMETEK Lloyd Instruments Ltd., Fareham, UK) with the following parameters: maximum cell load 10 kg, target load 10 g, target value 25 mm, and target speed 2.0 mm/s. Cross-sections of the samples were placed midway to the blade.

2.3. Chemical properties of brine

During APP treatment, a small amount of brine (approximately 1.5 mL) remained on the surface of the marinated pork. This sodium nitrite-free brine was collected after APP treatment, as was the sodium nitrite-added brine before drying (see the first group in Fig. 1). The nitrite content and pH were analyzed immediately.

The collected brine was filtered through a 0.2-μm polyvinylidene fluoride syringe filter (Whatman PLC) and diluted with distilled water (1:200, v/v). Then, nitrite content was measured using an ion-chromatograph (Dionex ICS-3000; Dionex Corporation, Sunnyvale, USA) equipped with a dual eluent generator system, dual chromatography compartments with dual suppressed conductivity detectors, and dual gradient pumps. Samples were analyzed using a guard column, AG 20 (50 × 2.0 mm inner diameter, Dionex Corporation, Sunnyvale, USA) coupled with an IonPac AS20 (250 × 4.0 mm inner diameter, Dionex Corporation, Sunnyvale, USA) analytical column. The flow rate was 1 mL/min. Suppression was achieved using an ASRS URTRA II (4 mm) self-regenerating suppressor, and the injection volume was 25 μL. The

analyses were carried out with a gradient elution mode, beginning with 15 mM of potassium hydroxide for 8 min, then 40 mM from 8–18 min, and 15 mM from 19–20 min.

The pH of each brine was measured using a pH meter (SevenGo, Mettler-Toledo International Inc., Schwerzenbach, Switzerland).

2.4. Inoculation tests

2.4.1. Preparation of inocula and inoculation

Staphylococcus aureus (KCTC 11764) and *Bacillus cereus* (KCTC 3624) were cultivated in tryptic soy broth (Difco Laboratories, Detroit, MI, USA) at 37 °C and nutrient broth (Difco) at 30 °C, respectively. After 48 h, the cultures were centrifuged (2419 × *g* for 15 min) in a refrigerated centrifuge (Continent 512R). The pellets were washed twice with sterile saline and suspended in saline to a final concentration of 10^8–10^9 CFU/mL. For inoculation tests, each strain (0.1 mL) was inoculated onto marinated pork in the second group (see Fig. 1).

2.4.2. Microbial analysis

After APP treatment and drying, jerky samples (6 g) were blended with sterile saline (54 mL) for 2 min. Then, appropriate dilutions of the samples were prepared in sterile saline and plated onto selective medium. *S. aureus* were grown in Baird-Parker agar (Difco) containing egg yolk tellurite emulsion (Oxoid, Basingstoke, England), and *B. cereus* were grown in Mannitol egg yolk polymyxin agar (Oxoid) containing egg yolk emulsion (Oxoid) and polymyxin B supplement (Oxoid). *S. aureus* and *B. cereus* plates were incubated for 48 h at 37 °C and 30 °C, respectively. The results were expressed as log colony-forming units per gram (Log CFU/g).

2.5. Statistical analysis

All experimental procedures were repeated in four individual trials. One-way analysis of variance was performed with a completely randomized design using the General Linear Model procedure. Significant differences were identified with the Tukey's multiple-range test using Statistical Analysis System Release 9.4 (SAS Institute Inc., Cary, USA), at a significance level of $P < 0.05$.

3. Results and discussion

3.1. Development of cured color

3.1.1. Color and nitrosoheme pigment

With increasing APP treatment time, the L^*, a^*, and chroma values of the pork jerky gradually increased, whereas b^* decreased ($P < 0.05$, Table 1). In other words, increased APP treatment time made the jerky brighter and more distinctly red, but less yellow. Jerky made with APP for 60 min had the highest a^* value among the treatments, while jerky made with APP for 40 min had a comparable a^* value to (i.e., no significant difference from) jerky made with sodium nitrite.

Development of red (cured) color is important for meat products. Although consumers expect new meat products without synthetic nitrite addition, they also expect the appearance of these products to be similar to conventional meat products (Sebranek et al., 2012). Generally, the red color of meat products results from nitrosoheme pigments such as nitrosylmyoglobin and nitrosylmyochromogen (Honikel, 2008; Pegg & Shahidi, 2000). When nitrite is added to meat, which usually has a pH of 5.5–6.5, nitrous acid (HNO_2, $pK_a = 3.37$) is formed from nitrite. The nitrous acid is in equilibrium with its anhydride (dinitrogen trioxide, N_2O_3) as described as Eq. (1).

$$2HNO_2 \leftrightarrow N_2O_3 + H_2O \quad (1)$$

$$N_2O_3 + \text{ascorbic acid} \leftrightarrow 2NO + H_2O + \text{dehydroascorbic acid} \quad (2)$$

$$NO + \text{myoglobin} \rightarrow \text{NO-myoglobin} \quad (3)$$

The presence of endogenous reductants in meat or addition of reductants like ascorbic acid promotes the production of nitric oxide (NO; Eq. (2)). NO can bind to myoglobin to form nitrosylmyoglobin (NO-myoglobin; Eq. (3)), which is responsible for the distinct red color. With heating, nitrosylmyoglobin decomposes into globin protein and nitrosylmyochromogen, which displays a stable red color (Honikel, 2008; Møller & Skibsted, 2002; Pegg et al., 1997; Pegg & Shahidi, 2000).

We hypothesized that the increased a^* value of pork jerky made with APP treatment resulted from nitrosoheme pigment formation. Jung et al. (2017) reported that APP treatment, which generates reactive nitrogen species (RNS), resulted in the infusion of nitrite into meat batter composed of pork, water, and salt. Similarly, if nitrogen compounds such as nitrite were produced in pork by APP treatment, there could be a reaction between myoglobin and NO. Consistent with this notion, the nitrosoheme pigment content of pork jerky made with APP gradually increased with treatment time. There was no significant difference in nitrosoheme pigment content observed between jerky made with APP for 40 min and those made with sodium nitrite. The similar trends suggest that APP increased nitrosoheme pigment formation, resulting in an increased a^* value.

Meanwhile, previous studies have reported that the a^* values of frozen pork, raw pork loin, and raw pork decreased after treatment with a corona plasma jet using dried air, indirect plasma using processed air, and APP using helium gas, respectively (Choi, Puligundla, & Mok, 2016; Fröhling et al., 2012; Kim et al., 2013). The APP system, composed of a DBD source with ambient air, also decreased the a^* values of raw pork butt, even though nitrogen molecular spectra were observed in the emission spectrum of the APP discharge (Jayasena et al., 2015). Our conflicting a^* value results might be due to the pork being marinated instead of raw. In this study, a small amount of brine remained on the marinated pork during APP treatment. This brine was collected after APP treatment (see Fig. 1) and analyzed to further examine why nitrosoheme pigment formed in the pork jerky made with APP treatment.

Table 1
Surface color of pork jerky made with atmospheric pressure plasma (APP) and sodium nitrite.

Color parameter	APP treatment time (min)				Sodium nitrite	SEM[1]
	0	20	40	60		
L^* value	45.92^{b}	47.38^{ab}	47.57^{a}	47.66^{a}	47.62^{a}	0.338
a^* value	11.29^{c}	12.51^{c}	14.68^{b}	17.58^{a}	15.29^{b}	0.472
b^* value	16.44^{a}	15.89^{ab}	14.57^{b}	14.26^{b}	14.54^{b}	0.420
Chroma	19.95^{b}	19.58^{b}	21.22^{ab}	22.58^{a}	20.54^{ab}	0.564

$^{a–d}$Different letters within each row indicate significant differences ($P < 0.05$).
[1] SEM, standard error of the mean ($n = 20$).

3.1.2. Physiochemical properties of brine

Consistent with the lack of significant differences in nitrosoheme pigment content between jerky made with APP for 40 min and with sodium nitrite (Table 2), similar nitrite content was observed in the brine (sodium nitrite-free brine) treated with APP for 40 min and that with sodium nitrite (sodium nitrite-added brine) (Fig. 3 (a)). In addition, the nitrite content of the brine gradually increased with APP treatment time ($P < 0.05$). These results indicate that nitrite generated in brine treated by APP may cause nitrosoheme pigment formation in pork jerky.

In this study, the pH of the brine decreased with increasing APP treatment time (Fig. 3(b)). Generally, APP treatment results in lower pH in liquid (Oehmigen et al., 2010). When APP treatment was applied to deionized water for 2 h, the pH of the sample decreased from 7 to 2 (Jung et al., 2015). Along with the formation of nitrite in APP-treated water, dissolution of NOx in water leads to a decrease in pH, as described in Eqs. (4) and (5) (Machala et al., 2013).

Table 2
Physiochemical properties of pork jerky made with dielectric barrier discharge plasma and sodium nitrite.

Physiochemical properties	APP treatment time (min)				Sodium nitrite	SEM[1]
	0	20	40	60		
Nitroso-heme pigment (ppm of hematin)	1.40^{d}	13.84^{c}	29.92^{b}	40.04^{a}	28.40^{b}	1.728
Residual nitrite (mg/kg)	0.43^{d}	5.56^{c}	18.23^{b}	26.34^{a}	27.27^{a}	1.034
TBARS[2] (mg malondialdehyde/kg)	3.84^{a}	3.65^{ab}	2.84^{bc}	2.27^{c}	2.68^{bc}	0.225
Water activity	0.80	0.82	0.79	0.80	0.82	0.022
Shear force (N)	63.60	65.37	64.78	66.01	65.09	2.401

$^{a–d}$Different letters within a low indicate significant difference ($P < 0.05$).
[1] SEM, standard error of the mean ($n = 20$).
[2] TBARS, 2-thiobarbituric acid reactive substances.

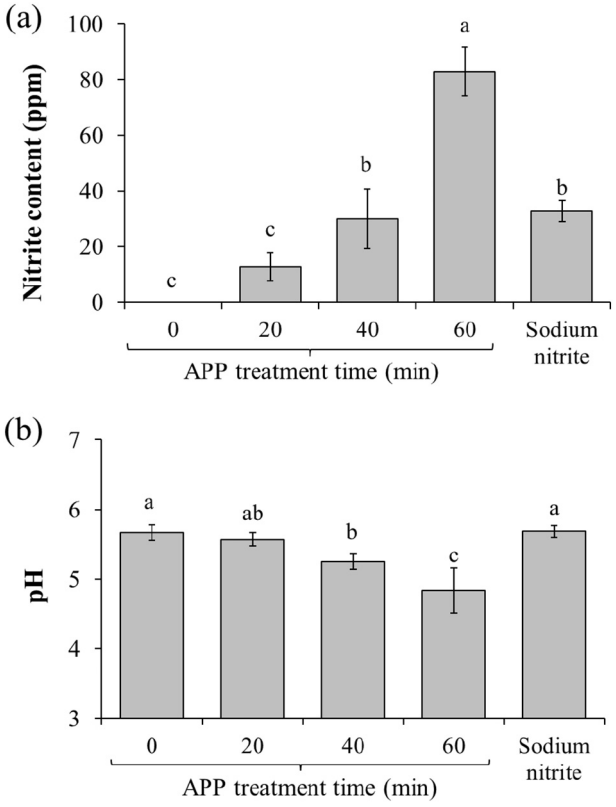

Fig. 3. (a) Nitrite content and (b) pH of the brine surrounding the marinated pork. $^{a–b}$Different letters indicate significant differences ($P < 0.05$). APP, atmospheric pressure plasma.

$$NO_2 + NO_2 + H_2O \rightarrow NO_2^- + NO_3^- + 2H^+ \quad (4)$$

$$NO + NO_2 + H_2O \rightarrow 2NO_2^- + 2H^+ \quad (5)$$

3.2. Residual nitrite content

Residual nitrite is the remaining nitrite in the final meat product that has not been converted to other substances. Residual nitrite content in meat products decreases when more nitrite is converted to nitrogen oxide and reacts with myoglobin to form nitrosoheme pigment (Alahakoon et al., 2015; Honikel, 2008). Interestingly, while the nitrite content of brine and nitrosoheme pigment content of pork jerky were similar in APP treatment for 40 min and sodium nitrite treatment, (Table 2, Fig. 3(a)), the residual nitrite content was significantly lower in pork in APP treatment for 40 min compared to sodium nitrite treatment (Table 2). To identify the reason for this observation, the nitrite content in brine was measured immediately after APP treatment.

Nitrite ($pK_a = 3.3$) can be progressively oxidized into nitrate under acidic conditions, as shown in Eq. (6) (Machala et al., 2013; Oehmigen et al., 2010)

$$3NO_2^- + 3H^+ + H_2O \rightarrow 2NO + NO_3^- + H_3O^+ \quad (6)$$

Braida and Ong (2000) reported that the rate of decomposition or oxidation of nitrite is dependent on the pH of the solution, with increased rates at low pH. In Fig. 3(b), the pH of the brines made with APP for 40 min and 60 min were 5.25 and 4.84, respectively, both significantly lower than the pH of brine treated with sodium nitrite (pH = 5.68). The decreased pH may explain why the nitrite content of the brine treated with APP for 40 min decreased more quickly, and the increased decomposition rate of nitrite (see Eq. (6)) would affect the residual nitrite content of pork jerky made with APP. However, further research is required to confirm this phenomenon.

Since the 1950s, laws have been established and authorities have regulated the amount of nitrite that can be used in meat products, as the lethal oral dose of nitrite is 33–250 mg/kg body weight in humans (Honikel, 2008; Schuddeboom, 1993). Thus, the added and residual nitrite contents generally allowed in meat products are 150 and 100 mg/kg, respectively (Honikel, 2008). In this study, the residual nitrite contents of all pork jerkies were below 30 mg/kg (Table 2). However, recent studies have revealed significant therapeutic benefits of nitrite, as a novel therapy associated with NO insufficiency (Parthasarathy & Bryan, 2012). Using a rationally designed nitrite-enriched dietary supplement has been shown to reduce hyperlipidemia in a clinical trial (Zand, Lanza, Garg, & Bryan, 2011).

3.3. Lipid oxidation

Generally, APP produces free radicals and reactive species that may compromise the functions of fatty acids, inducing lipid oxidation (Misra, Schlüter, & Cullen, 2016). When raw pork loin was exposed to APP with helium and oxygen gases, a significant increase in TBARS value was observed (Kim et al., 2013). Choi et al. (2016) reported that the peroxide value (POV) significantly increased in frozen pork upon corona discharge plasma jet treatment. Peroxides are one of the primary byproducts of lipid oxidation. The POV of commercial beef jerky was also significantly increased by 10 min of flexible thin-layer plasma treatment (Yong, Lee, et al., 2017).

In this study, however, TBARS values decreased as the APP treatment time increased (Table 2). The TBARS value of jerky made with sodium nitrite showed no significant difference with those of jerky made with APP for 20, 40, and 60 min. This result might be attributed to the antioxidant effect of nitrite. The TBARS value was the lowest in the pork jerky made with APP for 60 min, and the brine used in this treatment had the highest nitrite content.

In meat products, nitrous acid derived from nitrite sequentially forms nitrous acid anhydride and NO (Eqs. (1) and (2)). Because NO itself can be easily oxidized to NO_2 by reacting with oxygen, one of the antioxidative actions of nitrite is related to oxygen sequestering (Honikel, 2008). As described in Eq. (3), NO can also bind to the iron center of myoglobin, and this reaction can reduce lipid oxidation by reducing the amount of free iron available to initiate lipid oxidation (Parthasarathy & Bryan, 2012). Furthermore, NO acts as an inhibitor of the lipid peroxidation chain reaction by scavenging lipid peroxyl radicals (Hogg & Kalyanaraman, 1999; Pegg & Shahidi, 2000). Lee, Alford, Kannan, and Kouakou (2017) determined that the TBARS values of goat meat jerky cured with and without sodium nitrite were 4.26 and 6.81 mg malondialdehyde/kg, respectively.

3.4. A_w and shear force

The A_w of the pork jerkies ranged from 0.79–0.82 (Table 2), with no

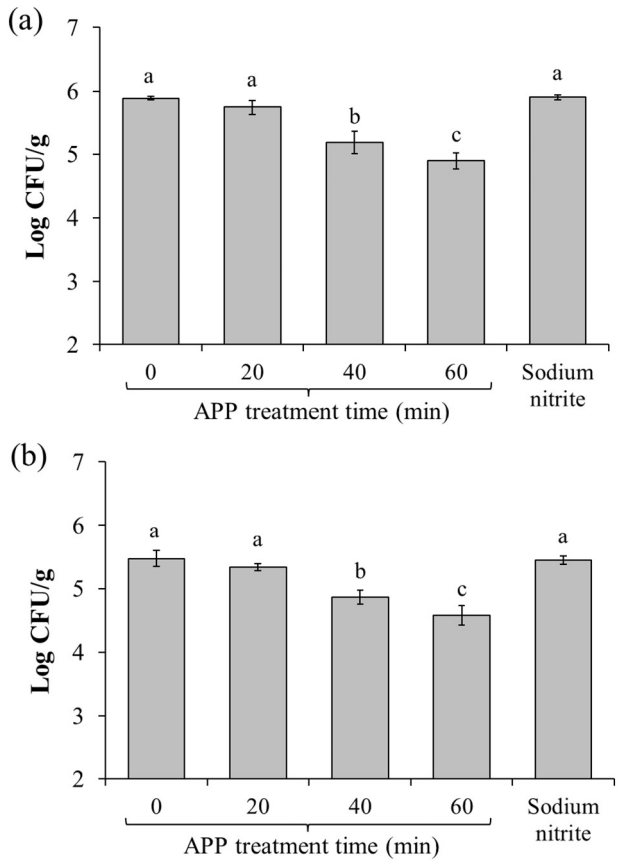

Fig. 4. The number (Log colony-forming units (CFU)/g) of (a) *Staphylococcus aureus* and (b) *Bacillus cereus* on pork jerky made with atmospheric pressure plasma (APP) and sodium nitrite, respectively. [a–b]Different letters indicate significant differences ($P < 0.05$).

significant differences between samples ($P > 0.05$). During the manufacturing process, it is important to control the A_w of jerky to avoid quality changes and microbial growth during storage (Lee, Alford, et al., 2017). The A_w is also useful for explaining the thermodynamic equilibrium state of jerky (Yang, Hwang, Joo, & Park, 2009).

In dried foods like jerky, texture is an important sensory attribute to consumers and it is highly correlated with Warner Bratzler shear force (Destefanis, Brugiapaglia, Barge, & Dal Molin, 2008; Lee, Alford, et al., 2017). The shear force values of pork jerky displayed no significant differences between treatments (Table 2). According to Lee, Alford, et al. (2017), the addition of nitrite does not affect the shear force value of goat meat jerky. Previous studies have also demonstrated that APP treatment does not influence the textural properties of meat and meat products. When raw pork butt and commercial beef jerky were exposed to flexible thin-layer plasma for up to 10 min, the texture parameters of the samples were not affected (Jayasena et al., 2015; Yong, Lee, et al., 2017). Similarly, Kim, Lee, Choi, and Kim (2014) reported that radio-frequency APP treatment does not influence the shear force value of beef jerky.

3.5. Inoculation tests

During pork jerky manufacturing, bacteria that have relatively low thermal death points are inactivated or destroyed at the drying temperatures. However, both *Staphylococcus* and *Bacillus* are thermoduric bacteria (Walsh, Meade, McGill, & Fanning, 2012), and therefore, *S. aureus* and *B. cereus* were selected to examine the antimicrobial effect of APP in pork jerky manufacturing. The number of *S. aureus* were 5.89, 5.74, 5.18, and 4.90 Log CFU/g, and the number of *B. cereus* were 5.47, 5.33, 4.86, and 4.58 Log CFU/g in pork jerky made with APP for 0, 20, 40, and 60 min, respectively (Fig. 4). Jerky made with sodium nitrite showed a significantly higher number of the pathogens than those made with APP for 40 and 60 min. As the nitrite contents of the jerky made with sodium nitrite and jerky made with APP for 40 min were similar, this suggests that compounds other than nitrite contributed to the antimicrobial effect.

APP is recognized as a novel non-thermal food processing technology that uses energetic, reactive gases to inactivate microbes on various foods. The bactericidal effect of APP is caused by a combination of multiple mechanisms (Niemira & Gutsol, 2011; Yong et al., 2015), including ROS production. The ROS produced by APP perniciously interacts with vital cellular molecules, such as proteins, enzymes, and DNA. Interaction between ROS and the cell membrane causes the formation of unsaturated fatty acid peroxides and oxidation of amino acids, potentially altering cell membrane function (Misra et al., 2016). Laroussi, Mendis, and Rosenberg (2003) reported that APP-initiated cell lysis through membrane disruption causes its antimicrobial effect. However, it should be noted that the bactericidal effect of APP would vary greatly depending on numerous factors, including the plasma discharge type, operating conditions, choice of gas, humidity, state of the sample, and the microorganisms present (Misra & Jo, 2017).

In this study, the use of APP showed the potential for pathogen inactivation as well as red color formation in pork jerky manufacturing. However, the role of the reactive species of APP in increase of lipid oxidation should be considered when it is applied for meat and meat products. Further studies are required to develop an optimally efficient APP system with increased bactericidal effect.

4. Conclusion

APP treatment produced nitrite from the remaining brine on marinated pork, which may affect the surface color a^* value and nitrosoheme pigment content in pork jerky. Jerky made with APP for 40 min showed no differences in L^*, a^*, and b^* values, nitrosoheme pigment, lipid oxidation, shear force, and A_w compared to jerky made with sodium nitrite (100 ppm of meat weight). In addition, the application of APP improved the microbiological safety of pork jerky. Therefore, APP could be a potentially safer alternative method for pork jerky manufacturing without using sodium nitrite.

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