**ABSTRACT** This study investigated the bactericidal effects of plasma-activated acetic acid (PAAA) on *Salmonella* Typhimurium and its impact on the physicochemical traits of chicken meat. Twenty milliliters of 0.8% (v/v) acetic acid (AA) was treated with plasma (2.2 kHz and 8.4 kVpp) for 30 min. The chicken skins, breasts, and drumsticks, inoculated with *S.* Typhimurium, were immersed in AA or PAAA and incubated for 10 min. The *S.* Typhimurium on the breasts and drumsticks were significantly susceptible to treatment with AA and PAAA, compared to the control group (deionized water treatment), and the population of bacterial cells in PAAA-treated chicken breasts and drumsticks decreased by 0.98 and 1.19 log CFU/g, respectively, compared with AA. The values for pH and 2-thiobarbituric acid reactive substances (TBARS) of PAAA-treated samples decreased significantly compared to the control group. The lightness ($L^*$) values of the chicken breasts after AA and PAAA treatments increased compared to the control group, whereas the value for yellowness ($b^*$) decreased. The scanning electron microscopic (SEM) images and the results for volatile compounds in chicken meat revealed similar patterns, with no significant differences between AA and PAAA treatments. In conclusion, we found that PAAA was more effective than AA and synergistic PAAA treatment of chicken caused to the reduction of *S.* Typhimurium and improve the meat quality. Therefore, PAAA could be utilized as a promising decontaminant for the chicken meat industry.

**Key words:** plasma-activated acetic acid, chicken meat, *Salmonella* Typhimurium, bactericidal efficiency, meat quality

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1Corresponding author: cheorun@snu.ac.kr

**INTRODUCTION**

With the increasing consumption of meat and meat products, the number of foodborne pathogen outbreaks related to meat has significantly increased (Zhao et al., 2001). Meat and meat products are highly susceptible to contamination by foodborne pathogens such as *Salmonella* spp., *Campylobacter* spp., Shiga toxin-producing strains of *Escherichia coli*, and *Listeria monocytogenes*, during their production, processing, and transportation (Nerín et al., 2016; Omer et al., 2018; Lee et al., 2021b). Particularly, chicken meat is a highly perishable product because of its characteristics that can cause rapid and intensive spoilage (Noriega et al., 2011). Most of the pathogen contamination in chicken meat can occur in slaughterhouses through spread of microorganisms between carcasses (Kim et al., 2019). A previous study reported that *Salmonella* spp. account for majority of the foodborne pathogens identified in poultry and poultry products (Domínguez et al., 2002). Therefore, many chicken meat industries face problems in the effective inactivation of *Salmonella* spp. as well as in ensuring that the quality of chicken meat is maintained. However, the inactivation of pathogens and deterioration of the quality of chicken meat remains a significant challenge (Dirks et al., 2012). Numerous efforts have been made to inactivate microbial contaminants in chicken meat using thermal treatments, use of bacteriocins or lactic acid bacteria, and washing with agents such as chlorine and trisodium phosphate (Mani-López et al., 2012). However, these traditional methods have some limitations in inactivating pathogens and adversely affect the nutritional value or sensory quality of chicken meat (Whyte et al., 2001; Kim et al., 2002; Berrang et al., 2007).

In many countries, organic acids such as acetic, citric, and lactic acid, which are designated by the European committee, FAO/WHO, and FDA as generally
recognized as safe substances (GRAS) for meats (Surekha and Reddy, 2000), are commonly used for the decontamination of chicken meat industries due to their antimicrobial potency, cost-effectiveness, and application simplicity (Cosansu and Ayhan, 2010). The antimicrobial traits of organic acids are based on their ability to lower the pH, thereby causing instability in the bacterial cell membranes (Reis et al., 2012). With the increasing consumer demand that industries reduce their use of chemical additives, many meat industries want to control the amount of organic acids used and simultaneously increase their antimicrobial effect in meat products (Sagong et al., 2011).

Recently, nonthermal technologies such as ultrasound, irradiation, ultra-high pressure, and pulsed light have been developed as alternatives to traditional methods (Heo et al., 2021). Cold plasma has a minimal impact on the quality of meat and meat products, is relatively inexpensive, and easy to install compared to other nonthermal technologies (Lee et al., 2016). In the present study, we prepared plasma-activated acetic acid (PAAA) by treating acetic acid with plasma (AA) to improve the bactericidal efficiency of AA. Some studies on LA treated with plasma have studied the synergistic bactericidal effects of meat (Qian et al., 2019, 2020). However, no study has been reported on the synergistically antibacterial effects of PAAA and the impact on the physicochemical traits of chicken meat.

The antibacterial effect and mechanism of acidic solution, such as acetic acid, obtained by treating plasma has also not been studied yet. Generally, reactive oxygen and nitrogen species (RONS) with a long half-life, such as $\text{H}_2\text{O}_2$, $\text{NO}_2^-$ and $\text{NO}_3^-$ may be the major antimicrobial agents and mediate a series of complex chemical reactions in plasma-activated water (PAW; Samukawa et al., 2012). However, Oehmigen et al. (2010) suggested that the synergistic action of RONS is potentiated under acidic conditions, which leads to enhanced antibacterial activity. Thus, the pH value affects the activity of reactive species in plasma-activated liquid. Additionally, $\text{NO}_2^-$ and $\text{H}_2\text{O}_2$ contribute to the formation of peroxynitrous acid (ONOOH), which is highly cytotoxic under acidic conditions (Lukes et al., 2014). During plasma discharge, $\text{H}_2\text{O}_2$ is utilized for the $\text{NO}_2^-$ dependent generation of ONOOH under acidic conditions (Lukes et al., 2014; Laurita et al., 2015; An et al., 2019). ONOOH is a powerful oxidant that can diffuse through cell membranes, damage cells, and promote cell death through apoptosis can necrosis (Huie and Padrnaja, 1993; Denicola et al., 1998). Considering the result that AA among organic acids has the highest sterilization efficiency against Salmonella Typhimurium (Mani-López et al., 2012), it is important to investigate the combined impacts on PAAA as a potential means for improving the efficiency of antibacterial activity. Our study could help to provide an understanding of the quality changes of chicken in the process of PAAA as a novel approach. Therefore, the objective of this study was to investigate the antibacterial effects of PAAA against S. Typhimurium and its impact on the quality characteristics of chicken meat.

MATERIALS AND METHODS

Bacterial Strains and Culture Preparation

S. Typhimurium (ATCC 13311) was obtained from the Korean Culture Center of Microorganisms (Seoul, Korea). S. Typhimurium was cultivated at 37°C in nutrient broth (Difco, Becton Dickinson Co., Sparks, MD) for 48 h to obtain mid-log phase cells. The strain was then washed twice with 0.85% NaCl solution (saline), followed by centrifugation at 2,266 × g for 14 min at 2°C (UNION 32R, Hanil Science Industrial, Co. Ltd, Gimpo, Korea). Finally, the viable cell density of the re-suspended culture was adjusted to approximately $10^8$ to $10^9$ CFU/mL using the optical density at a wavelength of 600 nm.

Sample Preparation, Sterilization, and Inoculation

Raw chicken skin, breasts, and drumsticks were purchased in advance from a local market in Seoul (Nonghyp Co., Seoul, Korea) and frozen at −20°C. Before the experiment, the samples were thawed overnight (24 h) at 4°C. The skin was punched into 2 cm² round pieces, and the breasts and drumsticks were cut into equal-sized pieces ($3.00 ± 0.05$ g) using a sterile knife. To study the antibacterial effect, the surface of each sample was exposed to ultraviolet light for 30 min to eliminate background microflora. Hundred microliters of the cell suspension were spot inoculated at nine different points on the surface of the samples and spread with a sterile spreader for even distribution and attachment. The samples were then placed for 1 h on a clean bench at room temperature (25°C) to allow bacterial adsorption to the surface of the samples.

Preparation of PAAA

As presented in Figure 1, an encapsulated atmospheric dielectric barrier discharge plasma, using a rectangular plastic container (137 × 104 × 53 mm) containing copper electrodes and a polytetrafluoroethylene sheet, was prepared for the generation of PAAA. Atmospheric air was used as the operating gas and plasma was generated at 2.2 kHz and 8.4 kVpp following the modified conditions from a previous study (Yoo et al., 2021). The AA immersed in a glass dish was
placed in the center of the container, and then exposed to plasma generated inside the container. PAAA was obtained by exposing the plasma discharge to 20 mL of AA (v/v) for 30 min. The concentrations of AA used in this study were 0.2, 0.6, and 0.8% (v/v), representing the corresponding AA concentrations in PAAA, respectively. The selected concentrations were based on preliminary studies. The bacterial cells in the samples treated with deionized water were used as a control (Royintarat et al., 2020). Additionally, based on our preliminary study, there was no significant effect on the detachment of bacterial cells of being washed away by immersing method.

**Microbial Analysis**

To investigate the bactericidal effect of bacteria, inoculated samples were immersed in 50 mL conical tubes containing AA and PAAA for each treatment and incubated at 25°C for 10 min (Royintarat et al., 2020). Immediately after plasma treatment, each sample was placed in a new tube containing 27 mL of saline solution. Each sample in tube was vigorously vortexed at high speed for 2 min for the detachment of bacteria on the surface of chicken meats. After the detachment of bacteria, the supernatants from each tube were serially diluted (1:10) in saline. Each diluted sample (0.1 mL) was spread on Xylose Lysine Deoxycholate agar (Difco) and agar plates were incubated at 37°C for 48 h for the determination of *S. Typhimurium* counts. The results of the skin were expressed as log CFU/cm², and the breasts and drumsticks were expressed as log CFU/g. The number of colony forming units per round pieces cm of the chicken skin, called the density, is found by Equation (1) (Hamilton et al., 2003).

\[
\text{Density} = \frac{\text{Avg count}}{\text{Drop volume}} \times \text{Dilution} \times \frac{1}{\text{Surface area}}
\]

Where Avg count is the average of the raw data counts [CFU], Drop volume is the volume of the drop plated [mL], Dilution is the 1/10⁻ᵏ where k is an integer for 10-fold dilutions, Volume scraped into is the volume of the liquid the chicken skin was scraped into [mL], Surface area is the scraped surface area of the chicken skin [cm²].

**pH Measurement**

The pH values of the breasts and drumsticks were measured according to a previously described method (Heo et al., 2021). After each treatment, 1 g of the homogenized sample was added to each tube containing 9 mL distilled water and mixed thoroughly for 30 s using a homogenizer (T25 Basic, Ika Co., Staufen, Germany). After homogenization, the solution was centrifuged (Hanil Science Industrial Co., Ltd.) at 2,265 × g for 10 min at 4°C and the pH value of the resulting supernatant was measured using a pH meter (Seven 2Go, Mettler-Toledo International Inc., Schwerzenbach, Switzerland).

**Lipid Oxidation Measurement**

The lipid oxidation of the breasts and drumsticks was analyzed according to a previously reported method, which calculates the level of 2-thiobarbituric acid reactive substances (TBARS) (Lee et al., 2016). Three grams of each sample and 9 mL of distilled water were mixed and homogenized with 50 μL of butylated hydroxytoluene (7.2% in ethanol) using a homogenizer at 9,600 rpm for 30 s. The homogenate (1 mL) was then added to a 15 mL centrifuge tube containing 2 mL of TBA (20 mmol/L)/trichloroacetic acid (15%) solution, and the tubes were heated in a water bath at 90°C for 30 min, followed by cooling in water. The test tubes were centrifuged at 2,265 × g for 10 min, and the absorbance of the supernatant was measured at 532 nm using a spectrophotometer (DU 530; Beckman Instruments Inc., Brea, CA). The TBARS value was presented as mg of malondialdehyde per kg sample, using a standard curve (Yim et al., 2020).

**Color Measurement**

The color of the breasts and drumsticks was measured using a colorimeter (CM-5, Konica Minolta Co., Ltd., Osaka, Japan) to obtain the CIE lightness (*L*), redness (*a*), yellowness (*b*), hue angle (tan⁻¹(*b*/*a*)), and chroma ((*a*² + *b*²)¹/²). The instrument was calibrated with a white and black standard tile before the analysis (Yoo et al., 2020). Measurements were taken randomly on the surface of the breasts and drumsticks at 6 different locations per sample with an 8 mm diameter measurement area. The color values were monitored by a computerized system using spectra Magic software (Konica Minolta Sensing, Inc.).

**EM Analysis**

The scanning electron microscopic (SEM) images of the breasts and drumsticks were obtained following the method reported in our previous study (Shin et al., 2020). After each treatment, the samples were cut into 0.5 cm diameter and 0.2 to 0.3 cm thick pieces and were fixed with Carnoy fluid (60% ethyl alcohol, 30% chloroform, 10% glacial acetic acid; v/v) at 4°C for 24 h. The samples were dehydrated using an increasing concentration of ethyl alcohol (70% for 12 h, 95% for 2 h, and 100% for 2 h). Each dehydrated sample was immersed in hexamethyldisilazane twice for 10 min and dried overnight (24 h) in a fume hood at 25°C. The dried samples were mounted on aluminum stubs using double-sided carbon tape and coated with a layer of platinum in a vacuum evaporator (EM AC E600, Leica Microsystems, North Ryde, NSW, Australia). Micrographs of the samples were visualized using a Zeiss Sigma field emission...
scanning electron microscope (AURIGA, Carl Zeiss Microscopy, Thornwood, NY).

**Electronic Nose Analysis**

The electronic nose (Heracles II, Alpha MOS, Toulouse, France) in each treatment was analyzed to determine the effect of PAAA on the odor of the treated chicken meat. The samples were ground using a meat grinder (MG510, Kenwood, Hampshire, UK), and each sample (5.00 ± 0.05 g) was taken in a 20-mL vial and cooked for 30 min at 80°C to obtain the volatile compounds (Li et al., 2020). The volatiles were then injected into an electronic nose equipped with dual columns of MXT-5 and MXT-1701 (10 m × 150 m × 0.4 m; length × diameter × thickness) (Restek, Bellefonte, PA). Each peak was integrated and identified using the retention time and relevance index, indicating the percentage of matching probability, based on the comparison of Kovats retention index of the detected compound and the Kovats retention indices of known compounds from the AroChemBase library (Lee et al., 2019).

**Statistical Analysis**

All experimental procedures were conducted independently in triplicates. The data were assessed by Tukey’s multiple-range test using the SAS program (version 9.4, SAS Institute Inc., Cary, NC) at a significance level of $P < 0.05$. Statistical analysis was performed using the Student’s $t$ test and one-way analysis of variance. The standard deviation of the mean values is reported in the figures and tables. Scores plot based on principal component analysis (PCA) was generated using MetaboAnalyst 4.0, in accordance with the method mentioned by Kim et al. (2020).

**RESULTS AND DISCUSSION**

**Antibacterial Effect of PAAA on Chicken Meats**

The population of bacterial cells in both AA and PAAA treatments significantly decreased with increasing concentrations of AA ($P < 0.05$, Figure 2A). The initial population of *S. Typhimurium* on the skin was 6.91 log CFU/cm². The population of *S. Typhimurium* decreased by 0.17, 1.05, and 2.33 log CFU/cm² after incubation for 10 min with 0.2, 0.6, and 0.8% PAAA, respectively. However, after treatment with AA, the population of *S. Typhimurium* decreased by 0.07, 0.93, and 1.23 log CFU/cm² under the same concentrations of AA (0.2, 0.6, and 0.8%), respectively.

The bactericidal efficiency of 0.6% PAAA ($P < 0.05$) and 0.8% PAAA ($P < 0.01$) were significantly higher than those of the control and 0.2% PAAA treatment groups. These data suggest that *S. Typhimurium* on chicken skin has a more significant susceptibility to PAAA treatment compared with that of AA, and it is significantly affected by the increasing concentration of AA. This provides a potential application in the slaughtering process. The reactive species in chemical reactions generated by plasma discharge induce lethal effects on bacteria due to the role of these short-lived species (Zhou et al., 2015). For solutions that were treated with plasma, the antibacterial effect of PAW is attributed to the acidic pH and ONOOH generated by H2O2 and NO2− (Naïtali et al., 2010; Öhmigen et al., 2011). Qian et al. (2019) also found that the number of *S. Enteritidis* inoculated on beef significantly decreased with increasing concentration of lactic acid in plasma-activated lactic acid (PALA), which can accelerate the generation of NO2−. Further, NO2− induces the generation of ONOOH with H2O2. Similarly, it showed the same trend in our study that the low pH values of 0.8% PAAA and the concentrations of H2O2 and NO3− increased significantly in 0.8% PAAA with the increase in plasma discharge time ($P < 0.05$) (data not shown). These findings may indicate that the formation of increased ONOOH, especially in liquids with pH lower than 4. In addition, because of the low pH of PAAA, there are more potential possibility to form acidified nitrates, possess strong cell toxic properties (Babaeva et al., 2012). Thus, the antibacterial activity of PAAA is also more potent with increasing concentrations of AA. As shown in Figure 2A, when the concentration of AA was 0.8%, the bactericidal efficiency and the level of significance for differences between PAAA and AA treatment were the highest ($P < 0.01$). Therefore, 0.8% AA concentration was regarded as the optimal treatment condition and was used to investigate the antibacterial activity of the chicken breasts and drumsticks.

Figure 2B shows the antibacterial effect of 0.8% AA and PAAA on the breasts and drumsticks. Each sample was incubated for 10 min with 0.8% AA and PAAA obtained by plasma exposure for 30 min. After treatment with AA, the population of *S. Typhimurium* on the breasts and drumsticks significantly reduced by 1.35 and 1.56 log CFU/g, respectively, compared with the control group ($P < 0.05$). Similarly, after treatment with 0.8% PAAA, the population of *S. Typhimurium* on the breasts and drumsticks significantly reduced by 2.33 and 2.75 log CFU/g, respectively ($P < 0.05$). These findings indicate that the susceptibility of the bacteria in chicken meat treated with PAAA was significantly higher than that treated with AA, which is consistent with the results of chicken skin presented in Figure 2A. According to a previous study, the efficacy of plasma was greatly reduced due to the surface topography on chicken skins, which may act as a physical barrier, resulting in the bacteria being protected from the reactive species generated by plasma, as compared to chicken muscle (Noriega et al., 2011). However, Rossow et al. (2018) identified that there were no significant differences in the bactericidal effects between the skin and breast samples by investigating the efficacy of parameters in plasma treatment. Consistent with this study, no significant differences in bactericidal effects
were observed between the skin and breast samples in our study. Therefore, these results suggest that *S. Typhimurium* can be effectively inactivated in chicken meat by treatment with PAAA.

**pH**

Table 1 presents the pH values of the breasts and drumsticks treated with AA or PAAA. The breasts and drumsticks showed significant differences between the control and treatment groups (0.8% AA and PAAA); the treatment group showed a decrease in pH values as compared to the control group. However, no significant differences were identified between the 0.8% AA and PAAA groups (*P* > 0.05). The decrease in the pH of chicken meat was related to the combined action of AA and PAAA. Aktaş et al. (2003) identified that the type and concentration of acids used significantly affected the pH values of marinated meat due to the dissociation of hydrogen ions (H⁺). The plasma-induced decrease in pH values in the samples was caused by the generation of acidogenic molecules from the plasma, resulting in their accumulation on the surface of the samples.

![Figure 2. Effect of acetic acid (AA) and plasma-activated acetic acid (PAAA) on population of *Salmonella* Typhimurium according to (A) the concentration of AA on chicken skins and (B) the antibacterial effects of 0.8% AA and PAAA on chicken breasts and drumsticks. Control group, deionized water treatment; AA, AA treatment; PAAA, PAAA treatment. Error bars represent standard deviation. **Different letters indicate a significant difference (*P* < 0.05) among the treatments. Student's *t* test; *, *P* < 0.05 and **, *P* < 0.01 with respect to the untreated control.](image)

| Treatments       | pH (Mean ± SD) | TBARS value (mg malondialdehyde /kg) |
|------------------|---------------|--------------------------------------|
| **Breast**       |               |                                       |
| Control          | 5.88 ± 0.01a  | 0.27 ± 0.02a                          |
| 0.8% AA          | 5.28 ± 0.02b  | 0.10 ± 0.01b                          |
| 0.8% PAAA        | 5.36 ± 0.18b  | 0.10 ± 0.01b                          |
| **Drumstick**    |               |                                       |
| Control          | 6.77 ± 0.03a  | 0.31 ± 0.03a                          |
| 0.8% AA          | 5.90 ± 0.02b  | 0.17 ± 0.02b                          |
| 0.8% PAAA        | 5.95 ± 0.08b  | 0.19 ± 0.04b                          |

Control, deionized water treatment; 0.8% AA, acetic acid (0.80%, v/v) treatment; 0.8% PAAA, plasma-activated acetic acid (0.8%, v/v) treatment. All values represent the Mean ± Standard Deviation. Different letters within column differ significantly (*P* < 0.05).
pH in the present study.

$$\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$$  \hspace{1cm} (2)

$$2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$$  \hspace{1cm} (3)

$$2\text{NO}_2 + \text{H}_2\text{O} \rightarrow \text{HNO}_2 + \text{HNO}_3$$  \hspace{1cm} (4)

**TBARS**

The TBARS values of the treatments (0.8% AA and PAAA) in breasts and drumsticks were lower than those of the control group (Table 1). Significant differences in TBARS values of the breasts and drumsticks were observed between the control and treatment groups. Several studies have shown a decrease in the TBARS value of meat treated with organic acids, such as acetic, lactic, and citric acid, compared with the control group. Kang et al. (2002) reported that TBARS values of pork treated with acetic acid were lower than those of the control group during storage, and this finding was supported by the inhibition of the generation of malonaldehyde, which is induced by products such as carbonyl complexes, alcohols, ketones, and aldehydes. According to previous research, the TBARS values of jerky treated with dielectric barrier discharge plasma decreased as the plasma treatment time increased, which was caused by the antioxidant effect of nitrite (Yong et al., 2019). On the other hand, the TBARS values of pork treated with plasma were slightly higher than those of untreated pork sample, indicating the result might be different due to the variations in fat content and fatty-acid composition of sample (Jayasena et al., 2015). In the present study, there were no significant differences in TBARS values observed between the 0.8% AA and PAAA treatments ($P > 0.05$), suggesting that the action of plasma has little effect on 0.8% PAAA treatment. Similarly, the differences of TBARS values between lactic acid and PALA were insignificant, demonstrating that plasma-activated liquids didn’t cause more severe lipid oxidation in beef samples (Qian et al., 2019).

**Color**

The color of meat is the most common indicator of quality, which has an important influence on consumer preferences (Wadhwni and Mcmahon, 2012; Kang et al., 2019). The $L^*$ values of the breasts and drumsticks treated with 0.8% AA and PAAA increased, whereas the $a^*$ and $b^*$ values decreased compared to those of the control group (Table 2). However, there were no significant differences in color values ($L^*$, $a^*$, and $b^*$) between the control group and the treatments (0.8% AA and PAAA) in drumsticks. These results indicate that both samples had similar patterns in $L^*$, $a^*$, and $b^*$ values, except for the significant differences. The color difference in meat is attributed to the amount of heme pigments and fibers type of predominant muscle (Berri et al., 2001). Lengerken et al. (2002) reported that breast meat contains more than 90% white fibers, whereas the proportion of red fibers and irregular surface color in leg meat is higher than in other meat types. This could be the reason why there were no significant differences among the treatments in drumsticks compared to the breasts. Stivarius et al. (2002) identified that ground beef treated with AA was lighter ($P < 0.05$; $L^*$) and less red ($a^*$) and yellow ($b^*$) ($P < 0.05$) in color compared to the control group. In addition, the ground beef from the treatment with AA showed higher hue angle values than the control group. Similarly, in the present study, the hue angles in the breasts and drumsticks were higher than those of the control group. These results were related to the concentration of oxymyoglobin in meat, and could be attributed to the discoloration of meat, which caused lower redness values and oxymyoglobin content after treatment with AA (Bell et al., 1986; Stivarius et al., 2002).

According to a previous study, the $L^*$ and $b^*$ values of chicken breasts treated with dielectric barrier discharge plasma also increased as the treatment time increased, whereas the $a^*$ value decreased significantly (Lee et al., 2016). Another study also identified significant increases in the $L^*$ values and significant decreases in the $a^*$ and $b^*$ values were observed in breasts treated with PAW (Kang et al., 2019). Fröhling et al. (2012) demonstrated that the hydrogen peroxide generated in plasma induced a green color in plasma-treated meats via reaction with myoglobin. Consistent with the previous discussion, the color of breasts and drumsticks treated with 0.8% PAAA was additionally affected by the action of plasma, although there were no significant differences between the 0.8% AA and PAAA treatments ($P > 0.05$).

**SEM**

The skin was removed from the surfaces of breasts and drumsticks for each sample; these showed a smooth and regular shape on the SEM images (Figure 3). As shown in Figure 3, there were no remarkable morphological alterations observed after treatment with AA or PAAA. However, compared to the control group in each sample, the images of AA or PAAA treatment clearly revealed the presence of pores. These could be correlated to the porous structure of chicken meat, which is caused by the weakening of structures under acidic conditions (Alagöz et al., 2020). Royintarat et al. (2020) identified that the combined treatment of PAW and ultrasound was more porous with the surface of chicken meat compared with individual treatment, resulting in bacteria being susceptible to PAW treatment. However, Lin et al. (2019) reported that the SEM images of eggs revealed less damage to the cuticles on eggs treated with PAW than on the commercially washed eggs. In the present study, no additional morphological changes were observed on the surface of PAAA-treated chicken breasts and drumsticks compared with the AA treatment. Thus, the morphological changes on the surface of chicken meat may not be attributed to the action of plasma in the present study.
Electronic Nose

Electronic nose is a rapid analysis tool to detect and distinguish between various types of gaseous samples (Chen et al., 2021). It is possible to obtain comprehensive information on volatile compounds in samples (Lee et al., 2021a). The PCA results obtained for the volatile compounds of chicken meat and are presented.

Table 2. Surface color values of breasts and drumsticks treated with acetic acid (AA) and plasma-activated acetic acid (PAAA).

| Treatments       | $L^*$     | $a^*$     | $b^*$     | Chroma   | Hue angle |
|------------------|-----------|-----------|-----------|----------|-----------|
| Breast Control   | 51.33 ± 2.00$^b$ | 3.15 ± 0.14$^a$ | 13.65 ± 0.20$^a$ | 14.01 ± 0.22$^a$ | 77.09 ± 0.46 |
| 0.8% AA          | 55.93 ± 1.43$^a$ | 2.08 ± 0.43$^{ab}$ | 10.40 ± 0.20$^{ab}$ | 10.65 ± 0.27$^{ab}$ | 78.65 ± 2.17 |
| 0.8% PAAA        | 58.56 ± 0.32$^a$ | 1.50 ± 0.80$^b$ | 9.90 ± 0.06$^b$ | 10.04 ± 0.10$^b$ | 82.55 ± 5.77 |
| Drumstick Control| 52.02 ± 1.60  | 8.97 ± 1.53  | 15.05 ± 0.76  | 15.99 ± 0.84  | 61.17 ± 5.35 |
| 0.8% AA          | 51.65 ± 6.04  | 7.88 ± 0.37  | 14.68 ± 2.63  | 16.71 ± 2.13  | 61.33 ± 5.56 |
| 0.8% PAAA        | 53.13 ± 2.90  | 7.45 ± 2.38  | 13.82 ± 0.72  | 15.75 ± 2.03  | 63.16 ± 6.38 |

Control, deionized water treatment; 0.8% AA, acetic acid (0.80%, v/v) treatment; 0.8% PAAA, plasma-activated acetic acid (0.8%, v/v) treatment. All values represent the Mean ± Standard Deviation.

$^a,b$Different letters within column differ significantly ($P < 0.05$).

Figure 3. Evaluation of morphological images of chicken meats using scanning electron microscope (SEM). (A) Control group (breasts) ($\times$ 2,000 magnification); (B) 0.8% acetic acid (AA) treatment (breasts) ($\times$ 2,000 magnification); (C) 0.8% plasma-activated acetic acid (PAAA) treatment (breasts) ($\times$ 2,000 magnification); (D) Control group (drumsticks) ($\times$ 2,000 magnification); (E) 0.8% AA treatment (drumsticks) ($\times$ 2,000 magnification); (F) 0.8% PAAA treatment (drumsticks) ($\times$ 2,000 magnification). Control, deionized water treatment; 0.8% AA, 0.8% AA treatment; 0.8% PAAA, 0.8% PAAA treatment. Bar, 10 $\mu$m.
in Figure 4. The two principal components (PC), PC1 and PC2, of chicken breasts and drumsticks well explained 81 and 79.2% of the overall variance, respectively. PCA is a simple method used for modeling and visualization of multidimensional data (Wiśniewska et al., 2016). PC1 was the most important variable for the different treatments (control, 0.8% AA, and 0.8% PAAA). As for chicken breasts presented in Figure 4A, PC1 separated control from 0.8% AA and 0.8% PAAA and accounted for 65.1% of the total variation, which indicated that there was a significant difference in odors between the control and the treatment groups. However, the difference between 0.8% AA and PAAA was not identified in the PC1 data area, indicating that they were not significantly different in odors. These results were equal to those of the drumsticks presented in Figure 4B. The overlapping area between 0.8% AA and PAAA in the results of drumsticks indicates that there were similarities of odor between 0.8% AA and PAAA treatments. Thus, the significant differences in odors between the control and treatment groups were mainly related to the action of AA, indicating that the changes in odor caused by the plasma treatment were negligible. Previous study found that 2.0% lactic acid treatment changed the odors of beef compared with 0.05 to 0.20% plasma activated lactic acid treatments (Qian et al., 2019).

In the present study, we identified the synergistic antibacterial activity of PAAA and its quality traits in chicken meat. PAAA showed a higher bactericidal efficiency than AA in breasts, drumsticks, and skin, and the bactericidal activity was proportional to the concentration of AA. Based on the 0.8% concentration of AA, which had a high bactericidal activity, there were no significant differences in the quality traits of chicken, including pH, surface color, and TBARS values between AA and PAAA treatments. Similar results were obtained for the morphological images and volatile compound areas analyzed by SEM and electronic nose analysis, respectively.

In conclusion, PAAA may be a potential decontaminating agent that can reduce foodborne pathogens such as S. Typhimurium on chicken meats. Considering the results of this study, PAAA can be a potentially useful agent in the industry to produce safer chicken meat products from the beginning. However, further studies are needed to evaluate the physicochemical, microbiological, and sensory properties of chicken meat after treatment with PAAA during storage and to assess mechanism of antibacterial effect against pathogenic bacteria including S. Typhimurium. In addition, the maximum volume of PAAA is limited in the present study, it is valuable to develop different treatment methods of PAAA other than immersion could be useful for industrial application.

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DISCLOSURES

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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