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Effect of plasma-activated organic acids on different chicken cuts inoculated with *Salmonella* Typhimurium and *Campylobacter jejuni* and their antioxidant activity

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ABSTRACT Lactic acid, gallic acid, and their mixture (1% each) were prepared (**LA, GA**, and **LGA**) and plasma-activated organic acids (**PAOA**) were produced through exposure to plasma for 1 h (**PAL, PAG**, and **PLGA**). Chicken breast and drumstick were immersed in the prepared solutions for 10 min and analyzed their antibacterial effect against *Salmonella* Typhimurium and *Campylobacter jejuni* and antioxidant activity during 12 d of storage. As a result, PAOA inactivated approximately 6.37 log CFU/mL against *S.* Typhimurium and 2.76, 1.86, and 3.04 log CFU/mL against *C. jejuni* (PAL, PAG, and PLGA, respectively). Moreover, PAOA had bactericidal effect in both chicken parts inoculated with pathogens, with PAL and PLGA displaying higher antibacterial activity compared to PAG. Meanwhile, PAOA inhibited lipid oxidation in chicken meats, and PAG and PLGA had higher oxidative stability during storage compared to PAL. This can be attributed to the superior antioxidant properties of GA and LGA, including higher total phenolic contents, $ABTS^{+}$ reducing activity, and DPPH radical scavenging activity, when compared to LA. In particular, when combined with plasma treatment, LGA showed the greatest improvement in antioxidant activity compared to other organic acids. In summary, PLGA not only had a synergistic bactericidal effect against pathogens on chicken, but also improved oxidative stability during storage. Therefore, PLGA can be an effective method for controlling microorganisms without adverse effect on lipid oxidation for different chicken cuts.

Key words: plasma-activated organic acid, chicken cut, bactericidal effect, antioxidant activity

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INTRODUCTION

Chicken is one of the most popular meats as it is a rich source of protein for human consumption (Baek et al., 2020; Agyemang et al., 2021). In addition, chicken meat has the advantage of being lower in fat content and price, and there are less restrictions by religious dietary practices compared to red meats (Ma et al., 2022). However, due to its nutrient-rich composition and high water content, everything is susceptible to contamination. The question is, if the bacteria survive and grow which is the problem with poultry meat. Microorganisms can contaminate chicken meat during its production, distribution, and consumption, leading to rapid food spoilage and potential foodborne illnesses (Kang et al., 2022b). *Salmonella* Typhimurium and *Campylobacter jejuni* are the most representative pathogens in chicken, which can cause food poisoning, such as salmonellosis and campylobacteriosis (Lin et al., 2019; Hatanaka et al., 2020; Kang et al., 2022a). Therefore, it is essential to develop efficient method for controlling microorganisms to ensure safe chicken meat.

Various nonthermal technologies (e.g., ultrasonication, irradiation, and high-pressure processing) have been attempted to control microorganisms in chicken, without heat denaturation and/or further quality deterioration (Zhuang et al., 2019; González-González et al., 2021). Plasma is one of the nonthermal technologies, comprising ionized gas composed of various reactive species (e.g., ion, electron, free radical, and UV photons) (Lee et al., 2011). It can efficiently inactivate

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microorganisms; however, plasma has limitations in industrial application due to its low penetration depth and nonuniform treatment (Chen et al., 2019; Domonkos et al., 2021). For these reasons, several studies have been conducted to expend its application (Jayasena et al., 2015; Baek et al., 2020; Heo et al., 2021). Among them, plasma-activated water (**PAW**) offers advantages due to this easy application to food in various forms, mass production feasibility, and cost-effectiveness (Zhou et al., 2020; Gao et al., 2022). PAW is defined as water that contains effective reactive species for microbial inactivation (Astorga et al., 2022). It has been approved for its effect on the different types of meat including chicken (Gao et al., 2022). However, PAW has limitations when applied to materials containing organic matter. The presence of organic matter may interfere with the reactions of reactive species in PAW, as it can modify the physicochemical characteristics of PAW (Xiang et al., 2019; Baek et al., 2020). Additionally, the application of PAW can lead to increase lipid oxidation (Kim et al., 2013; Jayasena et al., 2015).

To overcome some of the limitations of PAW, this study aimed to develop plasma-activated organic acid (**PAOA**) by combining plasma treatment with organic acids. Organic acids are widely recognized disinfectants used for food decontamination (Cruz-Romero et al., 2013). In this study, we selected lactic acid and gallic acid due to their demonstrated antibacterial and antioxidant activities (Kim, 1997; Kang et al., 2002; Asnaashari et al., 2014; Mohamed and Abdel-Naeem, 2018; Tian et al., 2022). Previous studies have explored the application of PAOA in chicken meat (Qian et al., 2021; Kang et al., 2022b). However, there is limited research on the utilization of PAOA involving gallic acid and/or its combination with lactic acid. Furthermore, there is a lack of studies in the bactericidal effect of PAOA on *C. jejuni*. Therefore, the objective of this study was to investigate the combined effect of plasma and organic acids on antibacterial effect in chickens and their oxidative stability during the storage period.

MATERIALS AND METHODS

Bacterial Solution Preparation

S. Typhimurium (ATCC 13311) and *C. jejuni* (NCCP 11192 were cultured using Nutrient Broth (Difco, Detroit, MI) and Muller Hinton Broth (Sigma-Aldrich, St. Louis, MO), respectively. Then, the broths were centrifuged at 4,001 $\times g$ at 4°C for 10 min (Combi 514R, Hanil, Incheon, South Korea). The supernatant was discarded, and the bacterial pellets were resuspended in 0.85% NaCl. This process was repeated twice. The final concentration of the bacterial solution was adjusted to 10^5 to 10^6 CFU/mL by appropriate dilution with 0.85% NaCl.

Sample Preparation

Plasma-Activated Organic Acids. For the preparation of PAOA, the atmospheric pressure dielectric barrier discharge plasma was used in this study. The container is made of zirconium material, and 1 L beaker was placed inside with a distance of 12 cm from its electrode. The beaker was filled with 200 mL of 1% lactic acid, gallic acid, and their mixture (1:1 v/v) in distilled water (**LA, GA**, and **LGA**, respectively). Then, following the method described by Lee et al. (2023), plasma was treated on the organic acids at 10 kHz and 4.0 kVpp for 60 min and plasma-activated LA, GA, and LGA were obtained for further applications (**PAL, PAG**, and **PLGA**, respectively). All organic acids (9.9 mL) prepared were promptly mixed with 0.1 mL of bacterial solutions containing *S.* Typhimurium and *C. jejuni*, respectively, within a 10 s period. The mixture was allowed to react at room temperature for 10 min and used for the analyses.

Chicken Meat Treated With Plasma-Activated Organic Acids. Chickens were purchased from a local market (Seoul, South Korea) and divided to breasts and drumsticks All the meat was consistently sliced into pieces of identical sizes (30 × 30 × 5 mm; 5.00 ± 0.05 g) using a sterilized knife and ruler, after which the weight of each sample was verified. A total of 162 breast and drumstick were prepared individually for the analyses of microbiological, antioxidant activities, and chemical properties. Then, the samples were immersed with and/or without PAOA for 10 min and stored at 4°C for 0, 6, and 12 d ($n = 3$ for each treatment). The immersion time was determined based on our preliminary test, and the storage period was established at 12 d to determine the maximum duration of the antibacterial and antioxidant effects of PAOA.

Antibacterial Effect

Prior to the PAOA treatment, the samples were exposed to ultraviolet light for 30 min using a 40 W UV-C lamp with a 253.7 nm to eliminate their endogenous microorganisms. Then, each solution (0.1 mL) of *S.* Typhimurium and *C. jejuni* was inoculated onto each piece and dried for 30 min to allow microorganisms to attach, and then they were immersed in the prepared organic acids and PAOA for 10 min.

After immersion with and/or without PAOA, each sample was transferred into a sterile bag containing 0.85% NaCl (45 mL). The remaining bacteria were detached from chicken meat using a stomacher for 2 min (Bag Mixer 400P, Interscience Co., St. Nom la Bretèche, France). Then, serial dilutions of PAOA and chicken meat were performed using 0.85% NaCl and their final dilutes with *S.* Typhimurium and *C. jejuni* (0.1 mL) were spread onto Xylose Lysine Deoxycholate agar plates (Difco, Detroit, MI) and Muller Hinton Agar (Sigma-Aldrich, St. Louis, MO), respectively. The agar plates were incubated at 37°C for 48 h and viable cells were expressed as log CFU/mL for PAOA and log CFU/g for chicken meat.

Antioxidant Activity

Total Phenolic Contents. Total phenolic contents were measured by the Folin-Ciocalteu's method

(Subramanian et al., 1965). In order to determine the total phenolic contents of PAOA, a mixture comprising 0.1 mL of the treatment solution and 0.2 mL of Folin-Ciocalteu reagent (Sigma-Aldrich, St. Louis, MO) was prepared. Subsequently, 3 mL of 5% sodium carbonate (Duksan Pure Chem, Ansan, South Korea) was added to the mixture. The resulting solution was thoroughly vortexed and incubated in the dark at 23°C for 2 h. Following incubation, the absorbance was measured at 765 nm using a spectrophotometer (SpectroMax M2e, Molecular Devices, Sunnyvale, CA). The obtained results were quantified based on a standard curve generated using gallic acid and expressed as mg gallic acid equivalent per mL (mg GAE/mL).

2,2′-Azino-di-(3-Ethylbenzthiazoline Sulfonate) ($ABTS^+$) Reducing Activity. Chicken breast and drumstick, respectively, were extracted by homogenizing with 15 mL of deionized water (**DDW**) for 1 min (T25 Basic, Ika Co., Staufen, Germany). The working solution of $ABTS^+$ was prepared by combining 14 mM of 2,2-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) diammonium with 4.9 mM of potassium persulfate in a 1:1 ratio (v/v). The working solution was diluted with ethanol to achieve an absorbance value of 0.70 ± 0.02 at 734 nm using a spectrophotometer (SpectroMax M2e, Molecular Devices). Then, 3 mL of the working solution was mixed with 20 μL of the solution and chicken meat extract. The mixture was incubated at room temperature in the dark room for 10 min and centrifuged at 2,268 × *g*, 4°C for 5 min (Continent 512R, Hanil Co., Ltd., Incheon, South Korea). Then, their absorbance was measured (SpectroMax M2e, Molecular Devices) and calculated based on Trolox as standard and expressed as mmol Trolox equivalent per g (mM TE/g).

2,2-Diphenyl-1-Picrylhydrazyl (DPPH) Radical Scavenging Activity. For DPPH analysis, 2 mL of a 0.2 mM solution of 2,2-diphenyl-1-picrylhydrazyl (**DPPH**) was added to the samples. The extraction of chicken meat was conducted following the procedure described in section $ABTS^+$ reducing activity. The mixture was vigorously vortexed and allowed to react for 30 min in the dark at room temperature. Then, the samples were centrifuged at 2,265 × *g* at 4°C for 15 min (Continent 512R, Hanil Co.) and their absorbance was measured at 517 nm using a spectrophotometer (SpectroMax M2e, Molecular Devices). The obtained absorbance values were calculated based on Trolox as standard and expressed as mmol Trolox equivalent per g (mM TE/g).

2-Thiobarbituric Acid-Reactive Substances. 2-Thiobarbituric acid-reactive substances (**TBARS**) values were measured by Lee et al. (2023) to assess lipid oxidation in chicken meat during 12 d of storage. After adding 15 mL of DDW and 50 μL of butylated hydroxy toluene to 5 g of the sample treated with each treatment solution, the samples were homogenized for 30 s (T25 Basic, Ika Co.). The homogenized samples were centrifuged at 2,265 ×*g* at 4°C for 15 min (Continent 512R, Hanil Co.), and the supernatant was filtered. Next, 2 mL of the homogenized sample was mixed with 4 mL of 20 mM 2-thiobarbituric acid and the mixture was heated at 90°C for 30 min using a water bath. After cooling the samples for 15 min, the mixture was vortexed and centrifuged at 2,265 × *g* for 15 min (Continent 512R, Hanil Co.). Then, the absorbance was measured at 532 nm using a spectrophotometer (SpectroMax M2e, Molecular Devices). The TBARS value was expressed as mg malondialdehyde/kg of meat sample.

Statistical Analysis

The experiment was performed for completely randomized design and the type of organic acids, plasma treatment, and storage day were considered as main factors. All analyses were observed in triplicate with 3 different times of manufacture for PAOA solutions. The data were analyzed using SAS software (version 9.4, SAS Institute Inc., Cary, NC) with statistical significance set at $P < 0.05$. Results were expressed as mean values and standard error of the mean. Statistical analysis was conducted using analyses of variance and Tukey's multiple comparison test.

RESULTS AND DISCUSSION

Plasma-Activated Organic Acids

Antibacterial Effect In bacterial solution, the initial numbers of *S.* Typhimurium and *C. jejuni* were 6.37 and 5.54 log CFU/mL, respectively. When organic acids and PAOA were treated on the bacterial solutions, the LA and LGA exhibited a higher bactericidal effect than GA against *S.* Typhimurium and *C. jejuni*, regardless of plasma treatment (Figure 1). In details, LA and LGA sterilized *S.* Typhimurium with a reduction of 6.37 log CFU/mL, while GA showed a microbial reduction of 4.34 log CFU/mL. In the case of *C. jejuni*, their reduction was the highest in LGA, followed by LA and GA. For both pathogens, the use of LA resulted in certain damage to the cell membrane and intracellular enzymes and proteins of microorganisms (Zhou et al., 2023), therefore, our result indicated the higher antibacterial effect by mainly LA addition. In other previous studies with organic acids, Jyung et al. (2023) and Stanojević-Nikolić et al. (2015) also reported the highest antibacterial effect of LA on different bacteria, including *Escherichia coli, Salmonella* Enteritidis, *Staphylococcus aureus, Listeria monocytogenes*, and *Bacillus cereus.*

When the organic acid and plasma were combined, the bactericidal effect of PAOA was increased against both pathogens, except for LA and LGA for *S.* Typhimurium (Figure 1). We did not observe significant changes in LA and LGA for *S.* Typhimurium as LA itself could sterilize all inoculated bacteria first. However, several studies had demonstrated that combined treatment of LA and plasma can enhance the antibacterial effect (Qian et al., 2019; Yadav and Roopesh, 2022). In this study, the presence of LA and LGA could have potentially improved the bactericidal effect when combined with plasma treatment, particularly if the initial

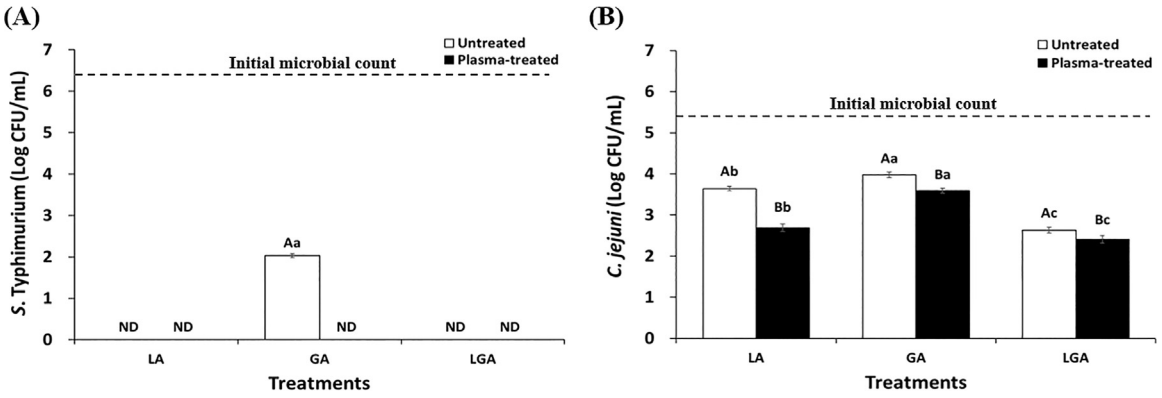

Figure 1. Inactivation effect of plasma-activated organic acids against *Salmonella* Typhimurium (A) and *Campylobacter jejuni* (B). LA, lactic acid; GA, gallic acid; LGA, mixed solution of lactic acid and gallic acid; ND, not detected. [A, B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same organic acid. [a–c]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments.

numbers of *S.* Typhimurium were higher. It appears that PAOA exhibited a synergistic interaction between the organic acids and plasma, likely due to the generation of reactive oxygen species (**ROS**) (Qian et al., 2021; Kang et al., 2022a). The PAOA consist of ROS composed of hydrogen peroxide, hydroxyl radical, and ozone (Kang et al., 2022a) and it can induce oxidative stress to bacteria, improving the bactericidal effect of PAOA (Theron and Lues, 2007; Zhou et al., 2020). Previous study has shown that the plasma device used in this study mainly generates reactive species such as hydrogen peroxide and ozone. These species are likely to dissolve in PAOA, potentially enhancing its sterilizing efficacy PAOA (Lee et al., 2023). These results were supported by the disk-diffusion assay (Figure S1). We found that all PAOA had larger clear zone in both pathogens, compared to organic acids alone. Meanwhile, regardless of organic acid and plasma treatment, *C. jejuni* exhibited a lower microbial reduction compared to *S.* Typhimurium, possibly due to the unique resistance mechanism of *C. jejuni* (Somers et al., 1994). When exposed to an antibacterial agent, *C. jejuni* utilizes its extracellular matrix to form a membrane with a distinct structure, making it difficult to penetrate into the bacterial cell (Somers et al., 1994).

Antioxidant Activities ***Total Phenolic Contents.*** Phenolic content plays a crucial role as an antioxidants activity by engaging in reactions with various free radicals (Aryal et al., 2019). It can contribute to antioxidant activity through the transfer of hydrogen atoms or single electrons, decomposition of peroxides, and chelation of transition metals (Zeb, 2020). In this study, no phenolic content was found in LA, but GA and LGA contained phenolic contents of 3.9 and 4.2 mg GAE/mL, respectively (Table 1). These results can be attributed to the addition of GA, which is a natural polyphenol product (Kim et al., 2006; Jung et al., 2010).

Plasma treatment increased total phenolic contents significantly in organic acids, except for LA (Table 1). In details, total phenolic content in GA and LGA was significantly increased by plasma treatment compared to that in organic acids. This increase in total phenolic content may be attributed to the response of ROS to GA. GA has been reported to induce the polymerization of phenolic compounds by facilitating the formation of carbon-carbon or carbon-oxygen bonds between gallic acid molecules through ROS-induced oxidative stress (Zahrani et al., 2020). This oxidative process also can lead to the production of quinone, which is a type of phenolic compound known for its antioxidant properties (Wang et al., 2019). Furthermore, when GA reacts with hydroxyl radicals, it can form a phenoxyl radical (Strlic et al., 2002). This phenoxyl radical can participate in oxidation-reduction reactions, generating new phenolic compounds and contributing to the overall increase in total phenolic content of GA (Strlic et al., 2002).

$ABTS^+$ Reducing and DPPH Radical Scavenging Activities. Regardless of plasma treatment, GA and LGA exhibited higher $ABTS^+$ reducing and DPPH

Table 1. Antioxidant activity of organic acid and plasma-activated organic acid.

	Total phenolic contents (mg GAE/mL)			ABTS (mM TE/mL)			DPPH (mM TE/mL)		
Types of acids	None	Treated	SEM[1]	None	Treated	SEM[1]	None	Treated	SEM[1]
LA	-[b]	-[c]	0.0000	$0.912^{A,b}$	$0.484^{B,b}$	0.0241	$0.135^{A,b}$	$0.078^{B,c}$	0.0112
GA	$4.284^{B,a}$	$5.120^{A,a}$	0.1098	5.455^{a}	5.455^{a}	0.0042	0.561^{a}	0.559^{b}	0.0006
LGA	$3.929^{B,a}$	$4.557^{A,b}$	0.0421	5.455^{a}	5.453^{a}	0.0013	$0.563^{B,a}$	$0.576^{A,a}$	0.0011
SEM[2]	0.0922	0.0268		0.0153	0.0128		0.0091	0.0013	

Abbreviations: GA, gallic acid; LA, lactic acid; LGA, mixed solution of lactic acid and gallic acid.
[1]Standard error of the mean ($n = 6$).
[2]$n = 9$.
[A,B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same or organic acid.
[a-c]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments.

radical scavenging activities than those in LA ($P < 0.05$) (Table 1). This difference could be induced mainly from addition of GA as it contains the abundant phenolic content. The positive relationship of phenolic contents with $ABTS^+$ reducing and DPPH radical scavenging activities have been reported (Zhao et al., 2008; Dudonne et al., 2009), as it can effectively neutralize free radicals and decrease its oxidative stress through direct reaction with free radicals (Jung et al., 2010). Hu et al. (2016) also stated that the phenolic hydroxyl group in GA can increase its $ABTS^+$ reducing activity by hydrogen and electron donation to free radicals. Furthermore, LA is known for its low antioxidant properties, including both $ABTS^+$ reducing and DPPH radical scavenging activities (Zhang et al., 2019).

When plasma was combined, we expected a synergistic effect on the antioxidant activity of PAOA as plasma treatment increased their phenolic contents (Table 1). However, only DPPH radical scavenging activity was enhanced in PLGA. This could be from various reasons, including the phenolic content in LGA. In addition, it was reported that DPPH radical scavenging activity can be increased with plasma treatment due to ROS generation (Ghasempour et al., 2020). PAG did not changed $ABTS^+$ reducing and DPPH radical scavenging activities, however, their values in PAL were even decreased with plasma treatment ($P < 0.05$). This may be due to the lack of phenolic hydroxyl groups with antioxidant properties in LA, unlike GA. And because of this, ABTS and DPPH values may have decreased due to oxidative stress caused by ROS generated by plasma. Taken together, GA and LGA have excellent antioxidant activity and PLGA, which is the combination of LGA and plasma treatment, had significantly higher antioxidant activity among the PAOA.

Plasma-Activated Organic Acid on Chicken Meat

Antibacterial Effect We applied different organic acids and PAOA to chicken meat (breasts and drumsticks) and analyzed their antibacterial effect during 12 d of storage (Figures 2 and 3). In chicken breast, the numbers of inoculated *S.* Typhimurium and *C. jejuni* were 5.89 and 6.09 log CFU/g, respectively (Figure 2). Immediately after the treatment, all organic acids and PAOA significantly decreased their numbers for both pathogens. Also, their effect was consistently maintained until 6 d. Specifically, LA and LGA exhibited a stronger antibacterial effect for both pathogens than GA, possibly by the addition of LA. This aligns with the results in Figure 1, suggesting the bactericidal effect of LA, compared to other organic acids (Stanojević-Nikolić et al., 2015). However, the treatment group containing GA exhibited a more substantial additional reduction effect compared to the group with LA during plasma combined treatment ($P < 0.05$). In addition, PLGA had certain synergistic effect on both *S.* Typhimurium and *C. jejuni* inoculated in chicken breast, regardless of storage days (excluding *S.* Typhimurium on d 12).

For chicken drumsticks, the initial numbers for *S.* Typhimurium and *C. jejuni* were 5.74 and 6.03 log CFU/g, respectively (Figure 3) Similar to Figure 2, the organic acids and PAOA demonstrated bactericidal effects against *S.* Typhimurium and *C. jejuni* inoculated in chicken drumsticks. LA and LGA exhibited a higher bactericidal effect than GA, which was sustained for up to 6 d. With plasma, PAG and PLGA tended to have synergistic bactericidal effect although chicken drumstick has different characteristics from breast. In fact, their effect on chicken breast and drumstick was relatively lower compared to that on the bacterial solution (Figure 1), possibly due to the presence of organic matter (Xiang et al., 2019). The proteins and nitrogen compounds of organic matter could reduce ROS concentrations by reacting with bacterial cells and ROS itself (Jo et al., 2018; Baek et al., 2020). However, despite of the limitations in chicken meat, their application can still effective for *S.* Typhimurium and *C. jejuni* and these results are comparable to the other studies (Qian et al., 2021; Zhao et al., 2021). Qian et al. (2021) and Zhao et al. (2021) investigated the antibacterial effect of PAL and resulted in a relatively lower effect on

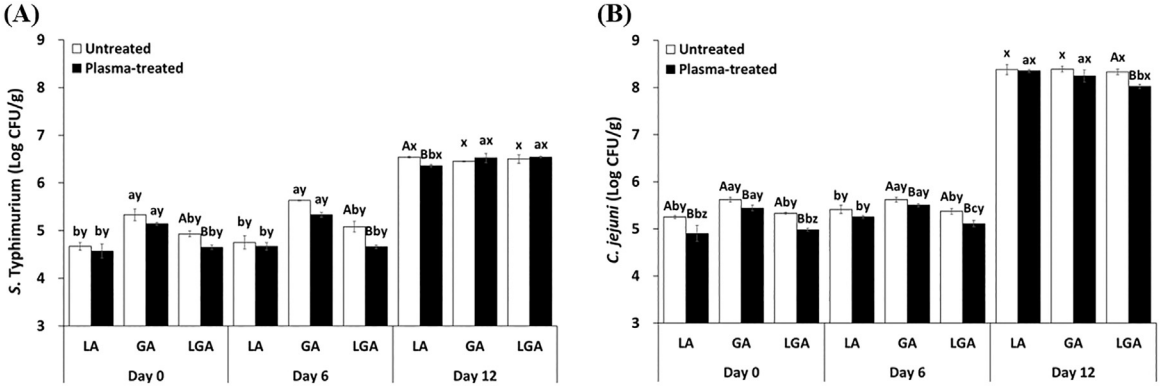

Figure 2. Inactivation of *Salmonella* Typhimurium (A) and *Campylobacter jejuni* (B) inoculated on chicken breast after immersion in plasma-activated organic acids. LA, lactic acid; GA, gallic acid; LGA, mixed solution of lactic acid and gallic acid. $^{A,\ B}$Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same organic acid. $^{a-c}$Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments. $^{x-z}$Different letters indicate significant difference ($P < 0.05$) between different storage days within the same treatment.

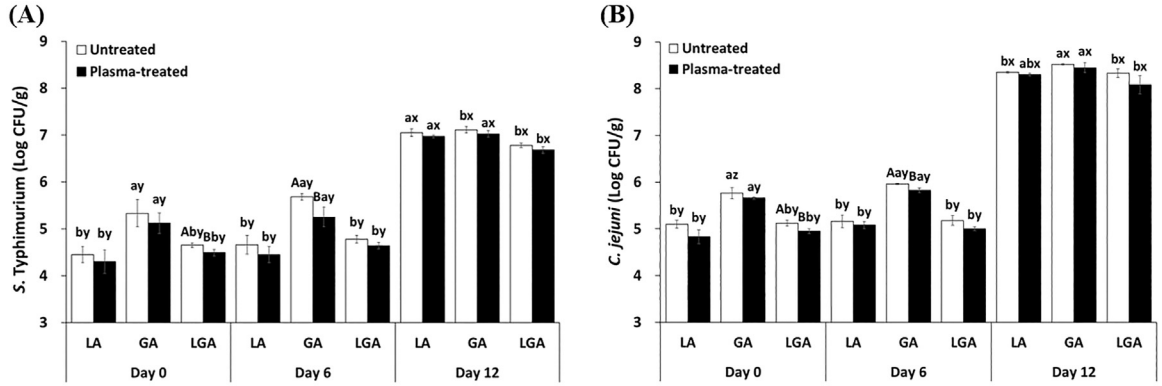

Figure 3. Inactivation of *Salmonella* Typhimurium (A) and *Campylobacter jejuni* (B) inoculated on chicken drumstick after immersion in plasma-activated organic acids. LA, lactic acid; GA, gallic acid; LGA, mixed solution of lactic acid and gallic acid. [A, B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same organic acid. [a, b]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments. [x–z]Different letters indicate significant difference ($P < 0.05$) between different storage days within the same treatment.

chicken drumstick and mackerel, respectively. Meanwhile, when examining the bactericidal effects of other nonthermal technologies, it was observed that ultrasound reduced *S.* Typhimurium by 0.48 log CFU/g and *C. jejuni* by 0.25 log CFU/g (Joo et al., 2020). Additionally, high-pressure processing reduced *S.* Typhimurium to less than 0.48 log CFU/g and *C. jejuni* to approximately 1.3 log CFU/g (Argyri et al., 2018; Iv et al., 2019). In comparison to these other nonthermal technologies, the bactericidal effect of PAOA was either similar or superior. In particular, the mixture of PLGA exhibited a more pronounced synergistic effect with plasma than other PAOA during the storage and was able to promote antibacterial effects even when applied to chicken cuts. Therefore, our results show that PLGA could be a potential method for controlling microorganisms in chicken meat.

Antioxidant Activities ABTS$^+$ Reducing and DPPH Radical Scavenging Activities. Similar to the results in Table 1, GA and LGA on chicken breast and drumstick exhibited higher ABTS$^+$ reducing and DPPH radical scavenging activities than LA alone, regardless of different storage days (Tables 2 and 3). In details, both breast and drumstick with GA and LGA had a significantly higher ABTS values compared to LA with/without plasma treatment involved (Table 2), possibly by the higher antioxidant activity in their solution (Table 1). Organic acid itself have antioxidant activity and GA is known for its excellent antioxidant capacity (He et al., 2020), which explains our findings with the GA and LGA. Their effect can be affected with plasma treatment (Ji et al., 2020). Here, plasma treatment changed the antioxidant activity of organic acids with different manners during storage days (Table 2). During the sixth day of storage in the breast and throughout the storage period in the drumstick, PAL exhibited significantly lower ABTS values compared to LA ($P < 0.05$). Conversely, in the breast, PAG and PLGA showed no significant alteration in ABTS values due to plasma treatment across all storage durations. In drumsticks, PAG and PLGA displayed either no difference or an increase in ABTS values post-treatment, except for PAG on the 12th day of storage. These varying effects of plasma on each PAOA may be attributed to the distinct

Table 2. ABTS$^+$ reducing activity (mM TE/g) of chicken meats treated with organic acid and plasma-activated organic acid.

		Breast			Drumstick		
Storage (d)	Organic acids	None	Treated	SEM[1]	None	Treated	SEM[1]
0	LA	$1.205^{b,x}$	$1.152^{b,x}$	0.0142	$1.253^{A,b,x}$	$1.116^{B,b,x}$	0.0180
	GA	$1.683^{a,xy}$	$1.683^{a,xy}$	0.0004	$1.681^{B,a,y}$	$1.683^{A,a,x}$	0.0005
	LGA	1.681^{a}	1.684^{a}	0.0008	$1.682^{a,y}$	1.685^{a}	0.0010
	SEM[2]	0.0099	0.0062		0.0012	0.0147	
6	LA	$1.146^{A,b,xy}$	$1.055^{B,b,y}$	0.0188	$1.136^{A,b,y}$	$0.944^{B,b,y}$	0.0085
	GA	$1.685^{a,x}$	$1.684^{a,x}$	0.0008	$1.684^{a,xy}$	$1.683^{a,x}$	0.0007
	LGA	1.684^{a}	1.685^{a}	0.0008	$1.684^{a,xy}$	1.685^{a}	0.0014
	SEM[2]	0.0153	0.0006		0.0065	0.0028	
12	LA	$1.094^{b,y}$	$1.066^{b,y}$	0.0097	$1.101^{A,b,z}$	$0.923^{B,b,y}$	0.0053
	GA	$1.680^{a,y}$	$1.679^{a,y}$	0.0017	$1.685^{A,a,x}$	$1.680^{B,a,y}$	0.0008
	LGA	1.685^{a}	1.682^{a}	0.0016	$1.688^{a,x}$	1.688^{a}	0.0003
	SEM[2]	0.0066	0.0048		0.0032	0.0031	

Abbreviations: GA, gallic acid; LA, lactic acid; LGA, mixed solution of lactic acid and gallic acid.
[1]Standard error of the mean ($n = 6$).
[2]$n = 9$.
[A,B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same or organic acid.
[a,b]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments.
[x–z]Different letters indicate significant difference ($P < 0.05$) between different storage days within the same treatment.

Table 3. DPPH radical scavenging activity (mM TE/g) of chicken meats treated with organic acid and plasma-activated organic acid.

		Breast			Drumstick		
Storage (d)	Organic acids	None	Treated	SEM[1]	None	Treated	SEM[1]
0	LA	$0.060^{B,b}$	$0.078^{A,b,x}$	0.0032	$0.061^{B,c,x}$	$0.070^{A,b,x}$	0.0005
	GA	$0.181^{B,a}$	$0.0185^{A,a}$	0.0005	$0.184^{a,x}$	$0.185^{a,x}$	0.0003
	LGA	$0.185^{a,x}$	0.183^{a}	0.0007	$0.176^{B,b}$	$0.184^{A,a}$	0.0009
	SEM[2]	0.0009	0.0026		0.0003	0.0008	
6	LA	$0.059^{B,b}$	$0.070^{A,b,x}$	0.002	$0.056^{B,c,y}$	$0.065^{A,b,y}$	0.0005
	GA	$0.181^{B,a}$	$0.185^{A,a}$	0.0007	$0.180^{B,a,y}$	$0.184^{A,a,y}$	0.0002
	LGA	$0.183^{a,y}$	0.182^{a}	0.0011	$0.176^{B,b}$	$0.184^{A,a}$	0.0001
	SEM[2]	0.0013	0.0010		0.0003	0.0002	
12	LA	0.055^{b}	$0.055^{b,y}$	0.0024	$0.051^{c,z}$	$0.051^{c,z}$	0.0010
	GA	$0.180^{B,a}$	$0.185^{A,a}$	0.0002	$0.180^{B,a,y}$	$0.183^{A,a,z}$	0.002
	LGA	$0.179^{B,a,z}$	$0.182^{A,a}$	0.0002	$0.174^{B,b}$	$0.181^{A,b}$	0.0007
	SEM[2]	0.0006	0.0019		0.0009	0.0004	

Abbreviations: GA, gallic acid; LA, lactic acid; LGA, mixed solution of lactic acid and gallic acid.
[1]Standard error of the mean ($n = 6$).
[2]$n = 9$.
[A,B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same or organic acid.
[a–c]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments.
[x–z]Different letters indicate significant difference ($P < 0.05$) between different storage days within the same treatment.

responses of individual organic acids during plasma treatment, and these distinctions could potentially impact lipid oxidation in chicken meat.

Meanwhile, GA and LGA also exhibited higher DPPH radical scavenging activity than LA, regardless of plasma treatment and storage days in breast and drumsticks ($P < 0.05$, Table 3). As shown in Table 1, GA possesses a high level of phenolic content, which contributes to its notable DPPH radical scavenging activity by enhancing the hydrogen ion donating ability of antioxidants (Dudonne et al., 2009). Therefore, chicken meats treated with GA and LGA generated a greater amount of DPPH-H, resulting in a significantly higher DPPH radical scavenging activity. Our result is accompanied with Limpisophon and Schleining (2017), who reported the effect of GA on the enhanced DPPH value in fish gelatin film. On the other hand, plasma treatment tended to improve DPPH radical scavenging activity in chicken meat during storage days. In the case of the breast, PAL and PAG consistently exhibited higher DPPH values compared to LA and GA throughout storage periods. Additionally, PLGA also demonstrated higher values than LGA on the 12 d of storage. For the drumstick, it is evident that PAOA consistently displayed higher DPPH values compared to organic acid alone during the entire storage period, except for PAG on d 0 and PAL on d 12. This observation can be attributed to the enhancement of endogenous antioxidant enzymes (e.g., superoxide dismutase, catalase, and glutathione peroxidase) in chicken meat (Chan et al., 1994). Plasma treatment can induce reactive species and improve their antioxidant activities (Dong and Yang, 2019; Bangar et al., 2022). It can change the aromatic residues of amino acid structured in the enzymes (Han et al., 2019). These findings suggest that the application of PAOA increased in the DPPH radical scavenging activity possibly by neutralizing reactive oxygen species.

Although ABTS and DPPH showed different tendency with plasma, PAG and PLGA consistently had a certain antioxidant activity, and the effect of PLGA was generally maintained during 12 d of storage. Therefore, the use of GA and its mixture, especially PLGA, can inhibit lipid oxidation in different chicken cuts.

Lipid Oxidation. Excessive lipid oxidation can affect the color, texture, nutrition, and flavor of meat and chicken meat is susceptible to lipid oxidation due to its high polyunsaturated acid content (Kang et al., 2002). In addition, free radicals have the potential to accelerate lipid oxidation, and plasma treatment can increase the generation of these free radicals (Jayasena et al., 2015). Therefore, we measured lipid oxidation in both chicken breast and drumstick during 12 d of storage using the malondialdehyde method (Table 4). In this study, LA resulted in the highest TBARS value in both cuts, whereas GA and its mixture decreased TBARS value for whole storage period. This may be by the differences in their antioxidant activity shown in Tables 2 and 3. In fact, the effect on GA on inhibiting lipid oxidation has been extensively investigated in previous studies. GA contains high phenolic content and can remove a large amount of oxygen derived free radicals as phenolic compounds can neutralize and scavenge free radicals (Das et al., 2012; Ramli et al., 2020). Also, Luo et al. (2023) reported that lipid oxidation in oyster was decreased with GA due to the antioxidant properties of alkyl esters in GA. Opposite to the effect of GA, LA is known for promoting lipid oxidation as it alters the intracellular oxidation state of lipid substances (Xu, 2009).

When plasma was combined, PAG and PLGA had a significantly lower TBARS values in both chicken cuts compared to that with PAL, except for drumstick on d 0 (Table 4). Overall, most treatments either maintained or reduced the TBARS value of chicken meat, except for d 0 PAL and d 6 PGA in the breast, as well as d 0 PAG and PLGA in the drumstick. This phenomenon could potentially arise from interactions with ROS and the antioxidant activity inherent in the PAOA solution. However, during storage, PAOA showed a lower rate of increase in TBARS values compared to each organic

Table 4. TBARS value (mg malondialdehyde per kg sample) in chicken meats treated with organic acid and plasma-activated organic acid.

		Breast			Drumstick		
Storage (d)	Organic acids	None	Treated	SEM[1]	None	Treated	SEM[1]
0	LA	$0.21^{B,a,z}$	$0.25^{A,a}$	0.010	$0.55^{a,y}$	0.57	0.016
	GA	0.15^{b}	0.15^{b}	0.007	$0.47^{B,b}$	0.53^{A}	0.010
	LGA	$0.17^{ab,y}$	$0.15^{b,y}$	0.010	$0.49^{B,b,z}$	0.54^{A}	0.011
	SEM[2]	0.010	0.008		0.010	0015	
6	LA	$0.29^{A,a,y}$	$0.24^{B,a}$	0.009	$0.60^{a,x}$	0.59^{a}	0.004
	GA	$0.15^{B,c}$	$0.17^{A,b}$	0.004	0.51^{b}	0.53^{b}	0.008
	LGA	$0.19^{b,xy}$	$0.18^{b,x}$	0.008	$0.53^{b,y}$	0.56^{ab}	0.013
	SEM[2]	0.008	0.007		0.007	0.011	
12	LA	$0.29^{A,a,x}$	$0.27^{B,a}$	0.004	$0.63^{a,x}$	0.61^{a}	0.023
	GA	0.17^{c}	0.17^{b}	0.005	0.52^{c}	0.54^{b}	0.009
	LGA	$0.22^{A,b,x}$	$0.18^{B,b,x}$	0.007	$0.58^{b,x}$	0.58^{ab}	0.004
	SEM[2]	0.007	0.004		0.009	0.018	

Abbreviations: GA, gallic acid; LA, lactic acid; LGA, mixed solution of lactic acid and gallic acid.
[1]Standard error of the mean ($n = 6$).
[2]$n = 9$.
[A,B]Different letters indicate significant different ($P < 0.05$) with and without plasma treatment within the same or organic acid.
[a–c]Different letters indicate significant different ($P < 0.05$) between organic acid treatments or PAOA treatments.
[x–z]Different letters indicate significant difference ($P < 0.05$) between different storage days within the same treatment.

acid without plasma treatment. Kang et al. (2022b) also reported that lipid oxidation did not increase when plasma-activated acetic acid was applied to chicken breast and drumsticks. It seems that the effect on PAOA on inhibiting lipid oxidation could be effective for longer period as ROS could be diminished with time (Gao et al., 2022) and only rely on their enhanced antioxidant activity thereafter.

On the other hand, a relatively higher TBARS value in drumstick than breast could be by their different characteristics (e.g., lipid content and fatty acid composition). This aligns with the findings of Gong et al. (2010) and Sahasrabudhe et al. (1985), who reported elevated lipid oxidation in the drumstick due to differences in fatty acid composition and higher lipid content. When organic acids were treated on drumstick alone, their lipid oxidation tended to increase with time, however, no significant changes were observed with PAOA. Thus, PAOA may delay oxidation rate in chicken meat especially for drumstick with long storage. Among them, PAG and PLGA had a higher oxidative stability during storage compared to PAL.

CONCLUSIONS

All organic acids inactivated *S.* Typhimurium and *C. jejuni* inoculated on chicken meat effectively and their effect was enhanced with plasma treatment. Specifically, PAL and PLGA had a higher effect on antibacterial activity compared to PAG. In addition, chicken meat treated with PAOA inhibited lipid oxidation for both chicken cuts during storage. Within the different PAOA, PAG, and PLGA resulted in a higher oxidative stability in chicken breast and drumstick than that with PAL.

Based on these results, PLGA had effective antibacterial effect as well as antioxidant activity. Considering that the primary antibacterial mechanisms of plasma involve the production of reactive species, concerns regarding oxidation are always present when applying plasma technology for food pasteurization. Therefore, we suggest PLGA as a promising method to control microorganisms without adverse effect on different chicken cuts.

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DISCLOSURES

There is no conflict of interest to declare.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.psj.2023.103126.

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