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*Research Article*

# In-Package Air Cold Plasma Treatment of Chicken Breast Meat: Treatment Time Effect

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The objective of this study was to investigate the effects of in-package dielectric barrier discharge (DBD) atmospheric cold plasma (CP) on meat color, microbiological quality and safety of chicken breast meat (pectoralis major). Raw broiler breast meat was collected from a local commercial plant. Noninoculated meat samples and meat samples inoculated with *Campylobacter* and *Salmonella* were packed in polymeric trays with air. The packaged samples were CP-treated at 70 kV for different times (0, 60, 180, or 300 sec) and stored at 4°C for 5 days. Microbial counts (psychrophiles, *Campylobacter, Salmonella*) and meat color (International Commission on Illumination (CIE) $L^*a^*b^*$) were measured before CP treatments and after 5 days of posttreatment storage. Psychrophile growth was inhibited ($P < 0.05$), and both food-borne pathogens were reduced ($P < 0.05$) by more than 90% with CP treatments regardless of treatment time. No differences in pathogenic bacterial counts were observed between the three treatment times; however, increasing treatment time beyond 60 sec resulted in additional inhibition of psychrophilic growth. There were no differences ($P > 0.05$) in $a^*$ and $b^*$ values between pretreatment and posttreatment plus storage; however, all CP treatments resulted in increased $L^*$ value ($P < 0.05$). Results indicate that in-package CP treatments can be used to reduce both microbial spoilage and food-borne pathogen risks, which could increase microbial food safety, although it may result in an overall paler breast meat, and the reduction (about 1 log) in pathogenic and spoilage microbes are limited.

## 1. Introduction

Microbiological quality and safety of raw poultry meat has been a challenge for the poultry industry. Nonthermal antimicrobial treatments, such as chilling with chlorinated water during processing, and strategies, such as cold-chain management and modified atmosphere packaging (MAP) postpackaging, are used to control microbial quality and safety of fresh poultry meat products during storage. However, they appear either not to be effective against microbial contamination postprocessing or to have limited effects on microbial control during postpackaging handling (marketing and distribution; for example, microbiological shelf life of fresh raw chicken meat is limited to 6–8 day at 4.4°C [1]). Each year, millions of pounds of fresh poultry meat products are lost as a result of microbiological spoilage [2]. In 2011, a potential *Salmonella* contamination resulted in a recall of 36 million pounds of ground raw turkey [3].

In-package dielectric barrier discharge (DBD) atmospheric cold plasma (CP) is a new nonthermal antimicrobial technique for inactivating food-borne pathogens and extending shelf life of fresh food products [4–8]. The CP system consists of two conductive electrodes separated with dielectric layers and a gas gap [4, 8–11]. At high voltage (more than 10,000 kV), this device generates a number of bioactive particles in packages, including reactive oxygen or nitrogen species (RONS, such as ozone, superoxide, hydroxyl radicals, atomic oxygen, nitric oxide, peroxynitrite), ultraviolet (UV), radiation energetic ions, and charged particles [12, 13]. Those particles confer bactericidal, fungicidal, and viricidal effects to the system [14]. For example, UV can cause DNA modification. Charged particles can

cause membrane rupture through electrostatic forces [15]. Guarnieri et al. [16] reported that RONS play a principal role in inactivation of microbes as compared to charged particles and UV in a DBD system. RONS interact with membranes and macromolecules (lipids, proteins, and DNA) and lead to injury and/or death of microbes [17]. The in-package CP allows for the treatment of food products inside sealed packages and eliminates the risk of postprocessing contamination.

A number of studies have documented the efficacy of the in-package DBD CP inactivation of microbes in food products. Misra et al. [6, 18] treated fresh strawberries with the in-package CP and reported that the background microflora (aerobic mesophilic bacteria, yeast, and mold) of strawberries was reduced by 2-log within 24 h of post-treatment, and the effect on product color and firmness was insignificant. Ziuzina et al. [7] treated cherry tomatoes with the same system and found that the treatment for 10, 60, and 120 s resulted in reduction of *Salmonella*, *E. coli*, and *L. monocytogenes* populations on tomatoes to undetectable levels from initial populations of 3.1, 6.3, and 6.7 $\log_{10}$ CFU/sample, respectively. Misra et al. [5] showed that there were no significant differences among weight loss, pH, and firmness between control and treated cherry tomatoes at the end of storage life. Kronn et al. and Wang et al. [4, 19] found that the CP with MAP resulted in more than 4-log reductions in microbial populations and extended microbial quality of fresh chicken meat products compared with untreated samples packaged in ambient air.

Rothrock et al. [11] demonstrated that the in-package CP treatment resulted in more than 2-$\log_{10}$ reduction in spoilage bacterium *Pseudomonas fluorescens* and pathogenic bacterium *Salmonella typhimurium* and more than 4-log reduction in pathogenic bacterium *Campylobacter jejuni* in liquid culture after samples were packed in air and treated at 80 kV for 180 sec. Changes in the CP treatment time significantly influenced CP killing efficacy. In this study, the effects of the CP treatments for different times were further evaluated on food-borne pathogenic and psychrophilic bacteria of packaged raw chicken breast meat (pectoralis major). The effect of the treatments on meat appearance was also estimated using surface color measurements.

## 2. Materials and Methods

*2.1. Meat Samples, Packaging, and Storage.* Boneless skinless breast meat (pectoralis major) from broiler birds (35–42 days old) was collected from a local commercial processing facility in Athens, Georgia. A total of 30 cutlets and 20 whole fillets were collected for each trial. Breast cutlets and fillets were transported on ice back to the laboratory and trimmed to remove fat and connective tissue. Prior to treatments, samples were placed in polymeric trays (19.5 cm × 14.5 cm × 4.0 cm, Sealed Air Corp., Duncan, SC, USA). Each tray contained two trimmed fillet cutlets (approximately 90.6 ± 6.5 g each) and two muscle samples (2.5 cm diameter, 2.5–3.0 cm thick, average weight 21 ± 1.5 g) cored from the cranial end of a single whole fillet (approximately 180.1 ± 30.2 g). One cutlet was placed in the tray skin/ventral side up and used for microbial analysis (psychrophiles). The other cutlet was placed in the tray bone/dorsal side up and used for surface color (International Commission on Illumination (CIE) $L^*a^*$ $b^*$) measurements. One of the muscle core samples was inoculated with *Campylobacter* and the other with *Salmonella* prior to being placed on the tray with the inoculated side up. Individual trays were sealed with a polypropylene-based barrier film (Toplex HB60, Plastopil Europe, Netherlands) in ambient air with a tray sealer (Koch Kats 100 Single Head Tray Sealer, Ultra Source LLC, Kansas City, Missouri, USA). After sealing, samples were let to sit for at least 45 min at ambient temperature so that the relative humidity in the package could reach >80% before CP treatments. After the CP treatments, packaged samples were stored in a 4°C cold room for 5 days before they were evaluated. In each trial, three trays were signed to each CP treatment. A total of three independent trials (with different batches of raw chicken breast meat and on separate dates) were conducted for the whole experiment.

*2.2. Inoculation with Food-Borne Pathogens Salmonella and Campylobacter.* One *Campylobacter jejuni* isolate and one *Salmonella typhimurium* isolate (both originally recovered from commercial poultry processing environments) were used during this study. The *C. jejuni* isolate was grown in Tryptic Soy Broth/Agar biphasic cultures incubated at 42°C, under a hydrogen-enriched microaerobic atmosphere (7.5% $H_2$, 2.5% $O_2$, 10% $CO_2$, and 80% $N_2$) for 24 h [20, 21]. The *Salmonella typhimurium* isolate was grown in Tryptic Soy Broth (TSB) at 37°C for 24 h at 200 rpm [22]. After incubation, 5 mL of the *C. jejuni* or *Salmonella typhimurium* growth was added to 495 mL of 1X phosphate buffered saline (PBS) to create the $10^6$ CFU/mL inoculum (average 6.6 ± 0.3 log10 for *Campylobacter* and 6.9 ± 0.4 $\log_{10}$ for *Salmonella*). Concentrations of *C. jejuni* and *Salmonella typhimurium* inocula were verified spectrophotometrically (OD600). The inoculation process began by pipetting 75 mL of inoculum into a plastic food tray (CS979, Cryovac, Duncan, SC). Fillet core samples were placed skin side down in each tray so that only the surface sat in the liquid. The core samples soaked for 30 min to allow the microorganisms to attach to the surface. After soaking, the core samples were removed and allowed to drip for 5 min before they were placed in the tray package [4].

*2.3. In-Package DBD CP Treatment.* The same in-package CP device as described by [4] was used in this study (Figure 1). The treatments were performed with a BK-130 AC dielectric test set consisting of a high-voltage transformer, power supply, and control system. Two 15.24 cm diameter spun-aluminum electrodes (Phenix Technologies, Accident, Md.) were connected to the high-voltage transformer. The two electrodes were arranged parallel to one another on the top and bottom of the sample. The electrodes were separated from the sample package by dielectric barriers and insulated from the bench with a yellow low-voltage electrical blanket (Velcro, 36 × 36 in, Class 0 Type 1, Salisbury standard rubber insulating blanket, Lab Safety Supply, Chicago, Ill.). The top

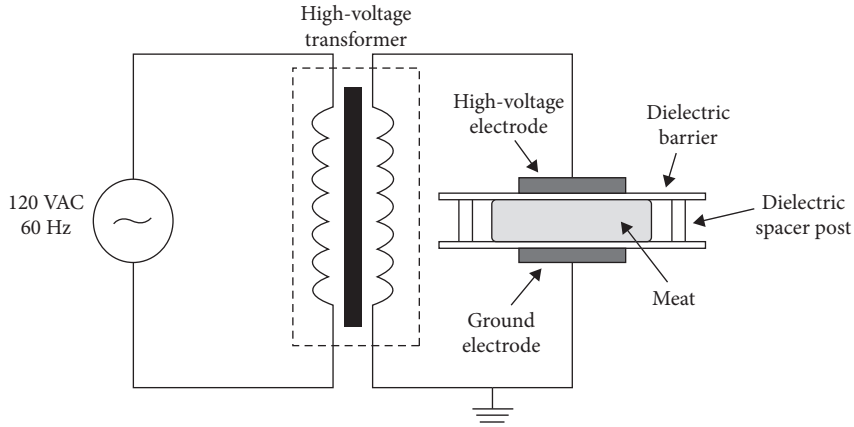


Figure 1: Schematic of in-package cold plasma treatment system.

electrode was connected to the 130 kV tap of the high-voltage transformer with a 1.09 m high-voltage spark plug wire (8.5 mm superconductor spark plug wire, MSD, El Paso, Tex.). For additional insulation, the high-voltage wire was fed through a 1.09 m length of Tygon tubing of 1.27 cm diameter. The bottom electrode was connected to the return terminal of the transformer with the supplied ground wire, and a jumper connected the ground and guard terminals (Figure 1). Before treatments, the system was warmed up with a sealed empty tray at 80 kV for at least 5 min. During the treatments, voltage and current (kV and mA) were monitored, and the beginning and end values were recorded to ensure treatment consistency. Average electric power was 58.5 ± 3.2 W for treatments.

After the meat sample was packaged and sat for more than 45 min, trays were individually treated in the CP device (Figure 1). In this study, only direct treatments (the package and sample are placed directly over the electrode) were tested. Once the tray was placed, the top dielectric barriers (polypropylene sheets) were positioned over the tray, and the electrode and electrode insulator were placed on top of the barriers [4]. Trays were treated for 0, 60, 180, or 300 sec. Temperature and humidity of the laboratory were recorded during every replicate of the experiment [23, 24].

*2.4. Ozone Gas Measurement.* Ozone gas was used as an indicator for DBD CP generation and antimicrobial activity within the package and commonly measured as a reference for the system performance [4, 7, 8, 19, 25, 26]. Immediately following CP treatment, headspace gas within the sample tray was taken and ozone content in the package was measured with Draeger gas detection tubes (Draeger Safety AG & Co., Lubeck, Germany). To measure high concentrations of ozone in packages, small gas sample volumes (≤3 mL) were collected with a 3 mL syringe. The syringe was flushed with headspace in the package once before gas samples were collected. The needle, which was used to collect ozone gas from package headspace, was removed, and the syringe was connected to a Draeger tube by a 3–4 cm length of flexible tubing. The tube was inserted into a Draeger Accuro detection pump (Draeger Safety AG & Co., Lubeck, Germany). The syringe volume was expelled into the detector tube and then removed, allowing a total flow volume of 100 mL to occur (volume required based on the manufacturer's instructions). The observed gas concentration was then multiplied by the ratio of the detection tube volume over the syringe volume [24]. It is important to note the ozone gas measured by the Drager Ozone Method relies on oxidation of indigo to form isatin [27]. This reaction is not specific to ozone, and many oxidative species will contribute to the "ozone" measurement including superoxide [28], nitrogen oxides [29], and peroxides [30].

*2.5. Microbial Analysis.* For microbiological recovery, the fillet cutlets or cores (including 3 extra cutlets and 3 meat cores inoculated with *C. jejuni* and 3 meat cores inoculated with *Salmonella typhinurium* for initial microbial load and the samples treated with CP and stored for 5 days) were rinsed with phosphate-buffered saline (PBS, Gibco by Life Technologies, Grand Island, N.Y.) 4 times less than that of meat weight (or about 22.5 mL for a cutlet and 5.25 mL for a cylinder). The PBS diluents were then serially diluted 4 times (~$10^7$ to $10^3$ CFU/mL). *C. jejuni* rinse dilutions were plated onto Campy-Cefex agar, *Salmonella typhimurium* rinse dilutions were plated onto Brilliant Green Sulfa agar (BGS) with 100 ppm nalidixic acid, and psychrophiles were plated onto TSA agar. *C. jejuni* plates and *Salmonella typhimurium* plates were incubated at the same temperature and atmosphere as described in section Inoculation with food-borne pathogens *Salmonella* and *Campylobacter*. For psychrophiles, the plates were incubated at 4°C for 10 days. Plates containing between 30 and 300 colonies were used for enumeration.

*2.6. Surface Color Measurement.* The surface color ($L^*a^*b^*$) on the bone-side surface of the chicken cutlets was measured using a spectrophotometer (CM-2600d, Konica Minolta, Inc., Tokyo, Japan) with settings of illuminant C, 10° observer, specular component excluded, and an 8 mm aperture. Color was measured before fillets were packed and after the samples were treated and stored at 4°C for 5 days. Surface areas free from obvious defects (bruises, discolorations,

hemorrhages, or any other conditions that might have prevented uniform color readings) were selected for measurements. Two measurements were taken for each fillet cutlet.

*2.7. Statistical Analysis.* Microbial count data were $\log_{10}$-transformed to normalize the data. Analyses of microbial and quality data were performed using one-way ANOVA via the PROC GLM of SAS (SAS version 9.4, SAS Institute Inc., Cary, NC). Replication was included as a factor. Means were separated using Tukey's multiple comparison tests at a significance level of 0.05.

## 3. Results

*3.1. Ozone Formation in Packages Immediately after CP Treatment.* Table 1 shows that ozone concentrations in meat packages treated with the in-package CP were greater ($P < 0.05$) than untreated packages immediately after DBD treatment at 70 kV regardless of treatment time. Increasing CP treatment time from 60 sec to 180 sec further increased ozone concentrations ($P < 0.05$) in packages; however, further increasing the treatment time to 300 s did not significantly increase ozone concentrations.

*3.2. Effects of In-Package CP Treatment Time on Microbial Populations.* The average populations of psychrophiles on raw fillet cutlets was 4 $\log_{10}$ CFU/mL before packaging and approximately 5 $\log_{10}$ CFU/mL for both *Campylobacter* and *Salmonella* on inoculated meat core samples (Table 2). After 5 days of refrigerated storage without CP treatment, the psychrophilic population significantly increased by ~4 logs (8.33 ± 0.07 CFU/mL; $P < 0.05$); however, *Campylobacter* and *Salmonella* populations were not significantly changed. Bacterial populations on CP-treated chicken breast meat were significantly lower ($P < 0.05$) than that on untreated fillets after 5 days of refrigerated storage, regardless of treatment time or bacterial type (Table 2). Cold plasma treatment for 60 sec resulted in more than 0.5-, 0.7-, and 0.4-log reductions in psychrophiles, *Campylobacter* and *Salmonella*, respectively, compared to nontreated samples ($P < 0.05$). Extending the CP-treatment times beyond 60 sec did not result in any further reductions in the *Campylobacter* or *Salmonella* populations; however, increasing CP-treatment time from 60 sec to 180 sec significantly reduced psychrophilic populations by an additional 0.6 logs. Increasing CP-treatment time did not further reduce psychrophilic populations on the breast meat.

*3.3. Effects of In-Package CP Treatment Time on Meat Color.* Of the three color measurements, only $b^*$ was significantly affected by the storage time (as noted by the ~2 unit increase in the nontreated control posttreatment sample) (Table 3). When comparing prepackaging to posttreatment readings (Table 3), there were no significant changes in the redness ($a^*$) or yellowness ($b^*$) of the CP-treated chicken cutlets for any treatment time, but significant increases in lightness ($L^*$) (by 3.1–3.6 units) were found for the 60, 180, and 300 sec treatment times. When comparing the effect of treatment time on the posttreatment measurements compared to the no-treatment control (0 sec + 5 d storage), increasing treatment time to at least 180 sec significantly increased $L^*$, while treatment times of 60 and 300 secs significantly reduced $b^*$. Redness estimates were unaffected by CP-treatment (Table 3).

Table 1: Effect of cold plasma treatment time on ozone formation (Draeger tube method) in chicken breast fillet packages (mean ± SE).

| Treatment (70 kV) | Ozone formation (ppm) |
|---|---|
| 0 sec | $0 \pm 0^{c}$ |
| 60 sec | $1850 \pm 240^{b}$ |
| 180 sec | $2650 \pm 145^{a}$ |
| 300 sec | $2550 \pm 189^{a}$ |

[a-c]Means within a column lacking a common superscript letter differ significantly ($P < 0.05$).

## 4. Discussion

The in-package CP device evaluated in this study is based on DBD technology. Dielectric barrier discharges are common methods used to generate plasma at atmospheric pressure [31] and are self-sustaining electrical discharges in electrode configurations containing an insulating material in the discharge path [32]. In DBD, the high electric field or voltage in the discharge gap causes formation of a large number of microdischarges and breakdown of gas molecules through electron-driven ionization and dissociation, creating reactive radicals. The dielectric between the electrode and discharge limits the amount of charge transported by a single microdischarge and distributes the microdischarges over the entire electrode surface area. In literature [5–9, 18, 31, 33], CP formation in packages treated with the same CP system was investigated using optical emission spectroscopy and oscilloscope. Excited species of $N_2$, NO, $N_2^+$, $O_2^+$, and OH group were detected in packages during DBD treatments, and it was concluded that the in-package CP system generated reactive oxygen species and excited nitrogen species. It was also demonstrated that the DBD performance or the DBD-induced CP formation was not affected by the presence of food materials in the packages.

Klockow and Keener [25] concluded that plasma generated from air by an in-package CP device similar to the one used in this study was characterized by generation of various chemically reactive species, with ozone being the most predominant, longest-living, and most oxidative species. Therefore, ozone formation in packages after the in-package CP treatment has been commonly used as an indicator for both CP formation and antibacterial activity [4, 7, 8, 18, 19, 25, 26]. Our study showed that the in-package CP device under the described experimental conditions is very effective in the generation of CP, resulting in antimicrobial activity in packages. Increased treatment times beyond 60 s could further increase the CP formation and enhance antimicrobial activity (especially psychrophiles).

Table 2: Effect of cold plasma treatment time on populations ($\log_{10}$ CFU/mL) of psychrophiles and pathogens on raw chicken breast fillets (mean ± SE).

| Treatment (70 kV) | Psychrophiles ($\log_{10}$ CFU/mL) | *Campylobacter jejuni* ($\log_{10}$ CFU/mL) | *Salmonella typhimurium* ($\log_{10}$ CFU/mL) |
|---|---|---|---|
| 0 sec + 0 time | $4.03 \pm 0.34^{d}$ | $5.14 \pm 0.14^{a}$ | $5.30 \pm 0.31^{a}$ |
| 0 sec + 5d storage | $8.33 \pm 0.07^{a}$ | $4.99 \pm 0.17^{a}$ | $4.90 \pm 0.16^{a}$ |
| 60 sec + 5d storage | $7.81 \pm 0.03^{b}$ | $4.20 \pm 0.18^{b}$ | $4.49 \pm 0.19^{b}$ |
| 180 sec + 5d storage | $7.18 \pm 0.12^{c}$ | $3.97 \pm 0.13^{b}$ | $4.42 \pm 0.21^{b}$ |
| 300 sec + 5d storage | $7.33 \pm 0.15^{c}$ | $4.03 \pm 0.16^{b}$ | $4.25 \pm 0.20^{b}$ |

[a-d]Means within a bacterial populations with no common superscript letter differ significantly ($P < 0.05$).

Table 3: Effect of cold plasma treatment time on CIE L*a*b* values of raw chicken breast fillets (mean ± SE).

| | L* | | a* | | b* | |
|---|---|---|---|---|---|---|
| Treatment (70 kV) | Prepackaging | Posttreatment + 5d storage | Prepackaging | Posttreatment + 5d storage | Prepackaging | Posttreatment + 5d storage |
| 0 sec | $56.9 \pm 1.0^{bcd}$ | $56.2 \pm 0.8^{cd}$ | $-0.31 \pm 0.49^{abc}$ | $0.21 \pm 0.20^{a}$ | $9.3 \pm 0.5^{b}$ | $11.0 \pm 0.3^{a}$ |
| 60 sec | $54.2 \pm 0.85^{d}$ | $57.8 \pm 0.7^{bc}$ | $-0.42 \pm 0.2^{abc}$ | $-0.05 \pm 0.13^{ab}$ | $8.7 \pm 0.4^{b}$ | $9.3 \pm 0.4^{b}$ |
| 180 sec | $59.2 \pm 0.6^{bc}$ | $62.5 \pm 0.7^{a}$ | $-0.80 \pm 0.13^{bc}$ | $-0.63 \pm 0.14^{abc}$ | $9.5 \pm 0.3^{ab}$ | $9.8 \pm 0.5^{ab}$ |
| 300 sec | $56.6 \pm 1.0^{cd}$ | $59.7 \pm 0.7^{ab}$ | $-0.98 \pm 0.22^{c}$ | $-0.58 \pm 0.18^{abc}$ | $8.4 \pm 0.6^{b}$ | $8.51 \pm 0.5^{b}$ |

[a-d]Means with no common superscript letter within the same parameter differ significantly ($P < 0.05$). Note: the same chicken breast meat in each treatment was used for color measurements before packaging and after treatment and 5d storage.

However, increases in CP treatment time beyond 180 s at 70 kV did not result in further increases in ozone concentrations in the packages. Similar results have been found in different published studies with the same CP device [8, 19, 26]. The lack of a linear relationship between ozone formation in packages and CP treatment time could be ascribed to quenching by increased levels of water dissociation and to direct reaction of ozone with water, $N_2$, and/or other active components formed in meat packages with high relative humidity and longer treatment time [10, 31].

Our data demonstrate that an in-package CP system can significantly inhibit growth of spoilage microbes and reduce food-borne pathogens on raw chicken meat surfaces when packaged in air. This result is well in line with the findings published in the literature on antimicrobial effects of CP treatments. Kim et al. [34] found that total bacterial populations on sliced bacon packed in helium and the helium/oxygen mixture decreased by 1.89 and 4.58 log CFU per gram, respectively, after CP treatments. Rød et al. [35] reported reductions in *Listeria innocua* populations ranging from 0.8 to 1.6 log CFU per gram after 1 and 14 days of storage, respectively, in the CP-treated, ready-to-eat meat product. Noriega et al. [36] showed that an 8 min CP treatment gave 1-log reduction on chicken skin, and a 4-min treatment gave > 3-log reductions on chicken muscle. Jayasena et al. [13] found that, following a 10 min CP treatment, microbial load reductions in *Listeria monocytogenes*, *Escherichia coli* O157: H7, and *Salmonella typhimurium* were 2.04, 2.54, and 2.68 log CFU per gram in pork-butt samples and 1.90, 2.57, and 2.58 log CFU per gram in beef loin samples, respectively. With the same device, Kronn et al. and Wang et al. [4, 19] also showed that in-package CP treatments significantly reduce microbial growth of total aerobic populations on fresh chicken meat packed under MAP atmospheric conditions. In addition, data from the current study also showed that increasing CP treatment times from 60 to 300 sec does not impact antimicrobial effectiveness against food-borne pathogens; however, increasing treatment time to 180 sec significantly increases antimicrobial efficiency against psychrophiles on raw chicken meat. These results suggest that the antimicrobial effect of the CP treatment time may vary with bacterial type.

Although ozone has been hypothesized to be the main factor contributing to microbial inactivation with DBD CP treatments due to its known antimicrobial properties and its high content within packages [4, 7, 8, 24, 25, 37], data in this study suggest that the antimicrobial role ozone plays in in-package CP treatments may varies with bacteria type. Ozone may have more of an effect on spoilage microbes compared with food-borne pathogens. Vaze et al. [38] concluded that ozone alone might not be a major inactivating factors in CP treatments. With the same device, Rothrock et al. [11] did not observe consistent correlations between bacterial inactivation and ozone contents measured with the Draeger tube method. In fact, plasma chemistry has shown that gas discharges during CP generation can be a source of charged particles, ions, reactive gas species, radicals, and radiation (ultraviolet, infrared, and visible), many of which have biocidal properties [39, 40].

In-package CP treatments in this study consistently and significantly increased the lightness ($L^*$ values) of raw chicken meat but had no effect on redness ($a^*$) or and yellowness ($b^*$), regardless of treatment time used in the study. These results indicate that in-package CP treatment may cause changes in the appearances of skinless chicken meat and make raw meat look paler. The effects of CP treatments on meat color have been reported in the past and results showed that the effects varied by treatment/package conditions, meat types, and color parameters. Kim et al. [34] found that $L^*$ values of CP-treated bacon surfaces decreased at a higher input power and greater exposure time; $a^*$ values increased at a higher input power and greater exposure time

in helium gas packages; and $b^*$ values did not change when helium was used but increased at a higher input power under helium/oxygen mix. Moon et al. [41] did not observe any large differences in $L^*$, $a^*$, and $b^*$ values between CP-treated pork samples and the untreated controls. Increased $L^*$ value in CP-treated meat could be attributed to high gaseous ozone formation in packages after CP treatment. Published data have shown that gaseous ozone exposure increased $L^*$ value on the surface of chicken breast meat [42] and beef [43].

In conclusion, our data demonstrate that an in-package DBD CP treatment can significantly reduce both spoilage (psychrophiles) and food-borne pathogen (*Campylobacter* and *Salmonella*) populations by as much as 1 log on breast meat packaged in air. The antimicrobial effectiveness against food-borne pathogens is not influenced by cold plasma treatment time (from 60 sec to 300 sec) at 70 kV. However, for spoilage microbes, treatment time may affect the effectiveness of the antimicrobial packaging system. The CP treatment may affect the appearance of raw meat by making the surface paler in color. Further research is needed to minimize the effect of in-package CP treatments on meat color and further enhance its antimicrobial efficiency before it can be applied to extend shelf life of fresh poultry breast meat.

## Data Availability

The data used to support the findings of this study are included within the article.

## Additional Points

*Practical Applications*. In-package CP treatments at 70 kV significantly reduces both spoilage (psychrophiles) and food-borne pathogen (*Campylobacter* and *Salmonella*) populations by as high as 90% on raw meat surfaces. For food-borne pathogens, in-package CP treatment time for 60 s is as effective as for 300 s; however, for spoilage microbes, longer treatment times could be more effective. In-package CP treatment may result in significant changes to raw meat appearances.

## Disclosure

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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