Journal of Food Protection, Vol. 84, No. 10, 2021, Pages 1772–1783
https://doi.org/10.4315/JFP-21-107

Review

Application of Peroxyacetic Acid for Decontamination of Raw Poultry Products and Comparison to Other Commonly Used Chemical Antimicrobial Interventions: A Review

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MS 21-107: Received 13 March 2021/Accepted 1 June 2021/Published Online 4 June 2021

ABSTRACT

Poultry remains one of the top food commodities responsible for foodborne illness in the United States, despite poultry industry efforts since the inception of hazard analysis and critical control point to reduce the burden of foodborne illness implicating poultry products. The appropriate use of antimicrobial compounds during processing of raw poultry can help minimize this risk. Currently, peroxyacetic acid (PAA) is the most popular antimicrobial in the poultry industry, displacing chlorine compounds and others. The aim of this review was to compare the effectiveness of PAA to that of other antimicrobials for the decontamination of raw poultry carcasses and parts. Twenty-six articles were found that compared PAA with over 20 different antimicrobials, applied as spray or immersion treatments for different exposure times and at different concentrations. The most common comparisons were to chlorine compounds (17 articles), to lactic acid compounds (five articles), and to cetylpyridinium chloride (six articles). Studies measured effectiveness by reductions in native flora or inoculated bacteria, usually *Salmonella* or *Campylobacter*. PAA was found to be more effective than chlorine under most conditions studied. Effectiveness of PAA was higher than or comparable to that of lactic acid compounds and cetylpyridinium chloride depending on product and treatment conditions. Overall, the results of primary literature studies support the popularity of PAA as an effective intervention against pathogenic bacteria during poultry processing.

HIGHLIGHTS

- Overall, PAA is more effective than chlorine for poultry decontamination.
- LA can be as effective as PAA, depending on the poultry application.
- CPC is less effective than PAA for poultry applications.
- More antimicrobials are proposed as PAA alternatives, but comparison data are limited.

Key words: Chemical antimicrobials; Decontamination; Peroxyacetic acid; Poultry products; *Salmonella*

Raw poultry products are susceptible to contamination with *Campylobacter, Salmonella,* and other pathogenic bacteria during live-animal rearing and slaughter operations. Between 2009 and 2015 in the United States alone, contaminated chicken caused 123 (10%) of 1,281 outbreaks for which a single food category could be identified *(13)*. During that period, chicken was the commodity responsible for the third-highest number of outbreak-associated foodborne illnesses (3,114 illnesses, 12%), making poultry products a concern for food safety *(13)*.

The Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA-FSIS) monitors the national prevalence of pathogens in poultry carcasses and parts. Between October 2019 and September 2020, the estimated national presence of *Salmonella* and *Campylobacter* in chicken parts in relation to production volume was 7.62 and 17.17%, respectively. *Salmonella* prevalence in whole carcasses was lower (3.52%) than in chicken parts, whereas *Campylobacter* percent positive in whole carcasses was similar (18.42%) *(53)*. USDA-FSIS data show that the prevalence of *Salmonella* and *Campylobacter* in raw chicken carcasses and parts has remained constant over the last few years. Between October 2018 and September 2019, the presence of *Salmonella* and *Campylobacter* in chicken parts was 8.77 and 17.60%, respectively, and the presence of *Salmonella* and *Campylobacter* in whole carcasses was 3.62 and 21.15%, respectively *(53)*. The implementation of appropriate pathogen reduction performance standards is expected to result in a reduction of illnesses from consumption of contaminated poultry products. Although contamination of raw carcasses cannot be completely eliminated, poultry processing establishments should aim to minimize contamination events by implementing appropriate sanitary dressing procedures and applying antimicrobial interventions during slaughter and

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fabrication of carcasses into parts *(54)*. The current performance standards for broiler carcasses allow for a maximum of 8 (15.7%) of 51 samples positive for *Campylobacter* and 5 (9.8%) of 51 samples positive for *Salmonella*. For chicken parts, the maximum for *Campylobacter* is 4 (7.7%) of 52 and, for *Salmonella,* 8 (15.4%) of 52 *(51)*. FSIS evaluates these standards over a moving window period of 52 weeks. Sampling frequency depends on the size and production volume of the establishment, among other factors *(51)*.

Multiple antimicrobial interventions for raw poultry products have been studied and reported. As a general rule, antimicrobial compounds should be approved for industry use, have documented efficacy at an appropriate level and contact time for a particular processing step, be cost-effective, and have minimal adverse effect on product quality *(1)*. For industry professionals, a pathogen reduction of at least one logarithmic cycle should be achieved for an intervention to be considered effective *(5)*. Traditionally, chlorine has been widely used as an antimicrobial due to its relatively low cost and low concentration required for efficacy *(58)*. Different chloride compounds, including aqueous chlorine dioxide (CD) and acidified sodium chlorite, have been tested and approved as alternative decontamination agents for raw poultry products. However, chlorine efficacy is quickly reduced by pH changes, high temperature, long residence times, and high concentration of organic matter *(7)*. Additionally, chlorine-based interventions are not approved in the European Union *(19)*. Other antimicrobials approved for use on poultry carcasses and parts in the United States include cetylpyridinium chloride (CPC), electrolyzed water, ozonated water, trisodium phosphate (TSP), and multiple organic acids, such as citric and lactic *(54)*.

Peroxyacetic acid (PAA), also known as peracetic acid or peroxyacid, is a mixture of peroxyacetic acid, octanoic acid, acetic acid, hydrogen peroxide, peroxyoctanoic acid, and 1-hydroxyethylidene-1,1-diphosphonic acid *(54)*. Its use in raw poultry products has been approved by the U.S. Food and Drug Administration (FDA) (21 CFR 173.370), with a maximum concentration of 2,000 ppm of peroxyacids and 1,435 ppm of hydrogen peroxide, depending on the application *(54)*. PAA can be purchased from several chemical suppliers around the world, either as a laboratory grade chemical or as a commercial formulation with specific instructions for use in poultry applications *(17, 26, 39, 47, 63)*. PAA should be stored in a well-ventilated place, in tightly closed containers that are protected from sunlight and kept away from other materials *(17, 63)*. Storage temperature varies for each commercial solution, from 2°C (35.6°F) to 25°C (77°F) *(47, 63)*. The concentration of commercial solutions ranges from 10 to 35.5% PAA, 30 to 60% acetic acid, and 1 to 15% hydrogen peroxide, although specific formulations can be trade secrets *(17, 47, 63)*. The rate of decomposition of PAA correlates positively with pH, temperature, and organic matter content, and negatively with initial PAA concentration *(9)*. At room temperature, a 40% solution of PAA will lose 1 to 2% of its active ingredients per month, but the shelf life of the solution can range from 6 to 12 months when stored at lower temperatures *(25)*. The presence of hydrogen peroxide makes PAA a strong oxidizing agent, with the ability to affect bacterial cell wall permeability, denature proteins and enzymes, and inhibit other cellular activities *(22)*. It has been demonstrated that PAA can act on the nucleotide bases of the DNA molecule *(25)*. It may also be capable of inactivating catalase, a detoxifying enzyme *(25)*. The combination of acidic and oxidizing properties of PAA makes it effective against a wide range of microorganisms *(1)*. In vitro, 7 to 11 ppm of PAA is enough to obtain a 5-log reduction in counts of both gram-negative (*Escherichia coli, Pseudomonas aeruginosa,* and *Salmonella* St. Paul) and gram-positive (*Bacillus subtilis, Enterococcus faecalis, Listeria monocytogenes,* and *Staphylococcus aureus*) organisms *(6)*. Additionally, PAA has some antimicrobial activity against viruses, bacterial spores, and fungi *(25)*.

Despite its proven antimicrobial efficacy, PAA has been implicated in occupational concerns because of its corrosive and irritating effect on eyes, mucous membranes of the respiratory tract, and skin *(33)*. Exposure to high concentrations of airborne chemicals can quickly overwhelm workers, with undesirable health outcomes that range from irritation to severe irreversible effects and even death *(34)*. In laboratory animals, lethal concentrations of PAA caused hemorrhage, edema, and consolidation of the lungs *(33)*. The U.S. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH) has set an immediately dangerous to life or health air concentration value of 1.7 mg/m^3 (0.64 ppm), because this concentration, over 30 min, is expected to be sufficient to cause slight to mild irritation and, potentially, to prevent escape from the situation *(34)*. There are currently no established occupational exposure limits for PAA by OSHA *(17, 47, 63)*. However, the American Conference of Governmental Industrial Hygienists has established an occupational exposure limit of 1.2 mg/m^3 (0.4 ppm) as a short-term exposure limit for inhalable fraction and vapor *(38)*. Occupational exposure limits for other ingredients present in PAA solutions, such as acetic acid, hydrogen peroxide, and sulfuric acid, have been established and should be considered during handling *(17, 47, 63)*. Implementation of containment units, adequate ventilation (approximately 10 air changes per hour), and process controls such as sensors are all strategies that the food industry may use to protect workers from overexposure to PAA vapors, mist, or droplets *(52, 63)*. Therefore, it is important to optimize the concentration of PAA throughout processing facilities in a way that achieves adequate microbial reductions without compromising employee safety and health.

Aqueous PAA solutions decompose into acetic acid and oxygen or hydrogen peroxide with fewer disinfection by-products than chlorine, which decreases its environmental impact *(8)*. PAA in poultry processing wastewater can cause problems in biological wastewater treatment processes, so that it is harder to meet effluent discharge requirements *(9)*. This is not expected during normal plant operation when residual PAA and hydrogen peroxide are not present. However, high levels of PAA or hydrogen peroxide, such as those expected when emptying chiller tanks or due to

accidental solution spills, can inhibit aerobic degradation and nitrification in wastewater bioreactors *(9)*. However, both reactions can recover quickly when PAA levels drop *(9)*.

In 2011, PAA was the predominant chemical used for postchill applications in the poultry industry *(10)*. More recently, Ebel et al. *(16)* surveyed 167 U.S. poultry establishments that produce both chicken carcasses and parts. The survey reported that most establishments use PAA as the main antimicrobial intervention, both for carcasses (124 of 167) and parts (146 of 167). Other establishments used CPC ($n = 23$), acidified sodium chlorite ($n = 9$), sodium hypochlorite ($n = 3$), chlorine ($n = 1$), CD ($n = 1$), and other interventions ($n = 6$) for chicken carcasses. For chicken parts, establishments used CPC ($n = 7$), chlorine ($n = 3$), sodium hypochlorite ($n = 3$), acidified sodium chlorite ($n = 1$), or others ($n = 5$). Two of the establishments did not apply any antimicrobial agents to chicken parts, and, in these, the prevalence of *Salmonella* was significantly higher than in the rest of facilities (41% versus 13 to 23%) *(16)*.

Current data and industry practice support the antimicrobial efficacy of PAA on chicken carcasses and parts when used at different steps of poultry production. The objective of this narrative review was twofold: (i) to identify the factors that determine the efficacy of PAA as a decontamination strategy during poultry processing and (ii) to compare the efficacy of PAA to that of other commonly used antimicrobial interventions in the poultry processing industry.

REVIEW METHODOLOGY

The review was carried out following recommendations from the European Food Safety Authority's document "Application of Systematic Review Methodology to Food and Feed Safety Assessments to Support Decision Making" *(18)*. The inclusion criteria for primary research studies was defined as follows: any scientific article reporting PAA as one of at least two chemical treatments applied to poultry carcasses or parts and the qualitative and/or quantitative effect those treatments had on microbial populations, either native or artificially inoculated, regardless of the study's geographical origin or publication date.

Scoping of the scientific literature was performed after formulating the review question. Inquiries were conducted on Scopus and ScIELO using the descriptors "peroxyacetic acid AND poultry," "peroxyacetic AND broiler," "peroxyacetic acid AND chicken," "peracetic acid AND poultry," "peracetic AND broiler," and "peracetic acid AND chicken" to search article titles, abstracts, and key words. After the initial exploration of the primary literature, the search was repeated the first week of every month until January 2021. All relevant primary research articles identified in English or Spanish were retrieved in full text through the University of Nebraska-Lincoln library system. Only scientific publications that reported qualitative or quantitative microbiological reductions directly attributed to PAA-based treatments and at least one other chemical intervention were used for data extraction. In total, 25 articles were found with the descriptors "peroxyacetic acid AND poultry," nine with "peroxyacetic acid AND broiler," 11 with "peroxyacetic acid AND chicken," 75 with "peracetic acid AND poultry," 23 with "peracetic acid AND broiler," and 58 with "peracetic acid AND chicken." All abstracts were read, and only those articles that met the inclusion criteria were selected for the following phase.

After elimination of duplicate articles, 26 full-text scientific publications (listed in the references) fulfilled the selection criteria and were read in their entirety by at least two authors prior to data extraction *(1, 2, 10–12, 14, 20, 24, 26, 30–32, 36, 37, 39–41, 43, 44, 46, 48, 50, 56, 60–62)*. The publication date ranged from 2004 to 2020, but most of the articles were published from 2013 onward. Twelve of the studies used whole carcasses as samples, whereas the rest studied different chicken parts, including breasts, legs, thighs, wings, frames, and chicken skin. Only one study used turkey drumsticks. Three of the studies further processed the treated parts to prepare ground chicken. Nine of the articles worked with the native microbiome of chicken, whereas the other 17 worked with inoculated samples. Immersion of the poultry products was the most common treatment (21 studies); only seven studies applied PAA as a spray. PAA was compared with chlorine and related compounds in 17 studies, to lactic acid (LA) and related mixtures in five studies, and to CPC in six studies. Additionally, PAA was compared with TSP (two studies), acidified sodium chlorite (ASC; four), citric acid (CA; one), alkyl dimethyl benzyl ammonium chloride (ADBAC; one), CD (two), lactic and citric acid blend (LCA; two), acidified LA (ALA; one), propionic acid (one), lauric alginate (LAE; two), lysozyme (one), 1,3-dibromo-5,5-dimethylhydantoin (one), sodium sulfate and sulfuric acid blend (Amplon) (SSS; three), ozone (two), PAA+T-128 chlorine stabilizer (one), PAA plus ozone (one), PAA plus sodium dodecyl sulfate (PAA plus SDS; one), PoultrypHresh (one), PAA and hydrogen peroxide mix (Sani-Date; one), hydrogen peroxide (one), and near-neutral electrolyzed water (NEW; one). Several studies reported comparisons of PAA with at least two other interventions.

The following information was identified from each publication: poultry matrix, target microbial population (*Campylobacter, Salmonella,* indicators, others), chemical treatment and process conditions (concentration, exposure time, method of application, temperature, etc.), sampling buffer, use of positive and/or negative controls, initial population counts, final population counts, and population reduction directly attributed to the chemical treatments. Regarding sampling buffer, most of the studies (10 of 26) used buffered peptone water (BPW) for initial rinse of samples. BPW was the standard solution proposed by the USDA for poultry sampling, until the agency adopted neutralizing buffered peptone water (nBPW) in 2016 *(21)*. The nBPW formulation includes BPW, sodium bicarbonate, sodium thiosulfate, and soy lecithin, which counteracts the carryover effect of oxidizing antimicrobials and improves recovery of *Salmonella* from poultry carcasses and poultry parts *(57)*. Only two studies, published in 2019 and 2020, used nBPW for sampling *(14, 36)*. Ten studies used BPW for sampling, whereas five studies used peptone water *(1, 10–12, 24, 30, 31, 37, 39, 41, 46, 50, 60–62)*. Interestingly,

five studies used modified BPW, adding neutralizing ingredients such as soy lecithin and sodium thiosulfate *(20, 26, 32, 48, 56)*. Neutralizing buffer, maximum recovery diluent, Dey-Engley neutralizing broth, and Bolton broth were used by one study each *(2, 40, 43, 44)*.

The sections below compare the effectiveness of PAA to that of chlorine-based compounds, LA, CPC, and other chemical interventions. As a reminder to the reader, only primary research articles that compared PAA with at least one other chemical intervention for decontamination of raw poultry carcasses or parts were used for data extraction and comparison.

EFFECTIVES OF PAA VERSUS CHLORINE-BASED COMPOUNDS

PAA treatment was commonly compared with chlorine-based interventions due to chlorine's status as the industry standard for chiller applications in the United States. Aqueous chlorine solutions produce free available chlorine in the form of hypochlorous acid and hypochlorite ions. Hypochlorous acid is more lethal to microorganisms than hypochlorite ions, so water pH must be lower than 7.0 to 7.5 to avoid the breakdown of hypochlorous acid into hypochlorite ions *(7)*. Hypochlorous acid has a destructive and nonselective oxidative effect, whereas hypochlorite ions inactivate bacteria by damaging the cell wall *(15, 29)*. Sodium hypochlorite solutions tend to decompose over time, and decomposition is promoted by heat, light, metal ions, water hardness, low pH, and the presence of soil *(3)*. The most stable sodium hypochlorite solutions contain less than 7.5% available chlorine and may have a shelf life greater than 30 days *(3)*. Sodium hypochlorite solutions sold as U.S. Environmental Protection Agency–registered sanitizers contain more than 7.5% available chlorine (usually 10 to 15%) but should be used within 30 days of manufacture, because a solution made with 12.5% initial chlorine concentration will have a 7 to 8% chlorine concentration after 30 days *(3)*. According to the USDA-FSIS, aqueous solutions of hypochlorous acid used for poultry processing should not exceed 50 ppm of free chlorine, and chill water dwell time should be between 10 s and 120 min. For PAA, the highest allowed level is 2,000 ppm for 5 to 30 s. Longer dwell times are permitted for lower concentrations of PAA, such as those used in chiller tanks *(54)*. Bauermeister et al. *(2)* compared the use of PAA (0.0025, 0.01, and 0.02% [25, 100, 200 ppm]) and chlorine (0.003% [30 ppm]) in a poultry chiller. After 1 h of treatment, all PAA concentrations significantly reduced *Salmonella* counts on inoculated carcasses compared with the chlorine treatment. The 0.02% (200 ppm) PAA treatment was the only one that significantly reduced *Campylobacter* counts, by 1.5 log CFU per sample, compared with the chlorine treatment. In a follow-up experiment, 0.02% (200 ppm) PAA treatment achieved significantly lower reductions than 0.003% (30 ppm) chlorine for *E. coli,* coliforms, and aerobic plate counts (APC), but no difference was observed in bacteria counts between treatments. PAA may be more effective than chlorine due to the low pH and the high presence of organic material in the chill water. The presence of organic material did not affect the effectiveness of PAA treatments, making it more attractive to the poultry industry *(2)*. A similar experiment with 400 noninoculated carcasses found that 85 ppm of PAA in the final poultry chiller (20-min dwell time) reduced the prevalence of *Salmonella* by 92% and the prevalence of *Campylobacter* by 43%, whereas reductions with 30 ppm of chlorine were only 57 and 13%, respectively *(1)*. On the other hand, Steininger et al. *(48)* compared the use of PAA (20 ppm) and chlorine (50 ppm) in a prechiller intervention for chicken carcasses and found similar counts of aerobic bacteria (3.95 versus 4.08 log CFU/mL rinsate), *E. coli* (2.02 versus 2.28 log CFU/mL rinsate), and total coliforms (2.56 versus 2.58 log CFU/mL rinsate). The concentration of PAA in this study was lower than in the others, which may explain why there was no difference compared with the chlorine treatment.

Outside of the United States, a study in Thailand found that *Salmonella* prevalence after chilling in a chlorine solution (unspecified concentration) for 45 min was 22.7%. A chilling simulation experiment with 0.5% (5,000 ppm) PAA resulted in a reduction of *Salmonella* prevalence of 5.0% *(56)*. In Australia, PAA immersion treatment (200 ppm, 20 min) was compared with chlorine immersion (50 ppm total available chlorine, 20 min) to reduce native *Campylobacter, Salmonella,* and total viable counts (TVC) on whole chicken carcasses at three different temperatures (4, 15, and 22°C) *(11)*. Chlorine treatment achieved a decrease in *Campylobacter* counts (0.1, 0.2, and 0.5 log CFU/cm^2, respectively) and TVC (reductions of 0.1, 0.1, and 0.5 log CFU/cm^2, respectively), but the change was not significant, whereas PAA achieved a significant decrease in *Campylobacter* (2.1, 2.6, and 1.8 log CFU/cm^2, respectively) but not in TVC (0.1, 0.1, and 0.0 log CFU/cm^2, respectively). Neither treatment achieved a significant reduction of *Salmonella* prevalence, which may be related to the low initial prevalence of this pathogen (0.2 to 0.4 most probable number per cm^2 of carcass). The use of PAA to replace sodium hypochlorite in Brazil was proposed by Guastalli et al. *(20)*. In this study, the authors simulated a prechilling processing step by immersing carcasses for 25 min in treatment solutions of sodium hypochlorite (5 ppm) and PAA (50 ppm). PAA reduced ($P < 0.05$) the psychrotrophic counts by 0.72 log CFU/mL compared with the water control (4.73 log CFU/mL average initial counts). There was no significant difference between chlorine and PAA treatment for mesophilic or coliforms counts, but an exposure time of 25 min is likely unrealistic for the poultry industry.

Two studies compared the use of PAA and chlorine in a postchilling tank, where exposure time is much shorter and antimicrobial concentration may be almost 10 times higher. Nagel et al. *(32)* compared 0.04% (400 ppm) and 0.1% (1,000 ppm) PAA to 0.004% (40 ppm) chlorine for chicken carcass treatment for 20 s. Reductions of *Salmonella* and *Campylobacter* counts with 0.04% (400 ppm) PAA were 2.02 and 1.93 log CFU/mL rinsate, whereas 0.1% (1,000 ppm) PAA achieved reductions of 2.14 and 2.03 log CFU/mL rinsate. Chlorine showed less than a 1-log CFU/mL rinsate reduction for both microorganisms and was significantly ($P < 0.05$) less effective than either concentration of PAA. Smith et al. *(46)* treated carcasses inoculated

with *C. jejuni* in a postchill tank for 60 s with PAA at 100 or 200 ppm, or with chlorine at 25 or 50 ppm. *Campylobacter* counts were significantly different ($P < 0.05$) among the chlorine treatment (5.38 log CFU/mL rinsate for 25 ppm and 5.22 log CFU/mL rinsate for 50 ppm), the 100-ppm PAA treatment (4.86 log CFU/mL rinsate), and the 200-ppm PAA treatment (4.15 log CFU/mL rinsate). When using a spray treatment instead of immersion, there was still a significant difference between counts of chlorine and PAA-treated carcasses, but no significant difference between the two concentrations of PAA (chlorine, 5.45 log CFU/mL rinsate for 25 ppm and 5.41 log CFU/mL rinsate for 50 ppm; PAA, 4.97 log CFU/mL rinsate for 100 ppm and 4.82 log CFU/mL rinsate for 200 ppm).

Overall, PAA may be more effective than chlorine for decontamination of *Campylobacter* and *Salmonella* in whole carcasses, in either prechill, chill, or postchill interventions, by immersion or spray application, when concentrations of PAA are higher than 85 ppm. Organic load, as low as 0.2% tomato extract or 0.5% bovine serum albumin, can drastically reduce the availability of free chlorine *(45, 59)*. Low temperatures in chillers slow down the penetration of chlorine into cell walls, so chlorine is generally ineffective when exposure is shorter than 1 h *(60)*. Not enough published information is available to draw conclusions about PAA's effect on other pathogenic microorganisms that may be present on chicken carcasses.

For chicken parts, antimicrobial treatments are usually delivered postchill by spraying or by immersion. Typical immersion conditions were used by Lemonakis et al. *(26),* who treated broiler carcasses and wings in 0.1% PAA (1,000 ppm) or sodium hypochlorite (67 to 69 ppm) for 30 s. APC and *Salmonella* and *Enterococcus faecium* counts for PAA-treated carcasses (4.3, 3.9, and 3.7 log CFU/mL rinsate, respectively) were significantly lower ($P < 0.05$) than those for chlorine (5.2, 4.7, and 5.0 log CFU/mL rinsate, respectively). Similar results were obtained with wings, for which PAA treatment resulted in 0.7, 0.8, and 0.7 log CFU/mL rinsate reductions in APC and *Salmonella* and *E. faecium* counts, respectively, compared with chlorine. The experiment was repeated with chicken wings inoculated with *C. jejuni,* with a 20-s sanitizer exposure through immersion or electrostatic spray *(44)*. PAA treatment achieved reductions in *Campylobacter* counts of 2.5 and 2.5 log CFU/g, whereas chlorine reductions were 1.6 and 2.2 log CFU/g by immersion and spraying, respectively. Both reductions were significantly lower ($P < 0.05$) than the initial load. In chicken drumsticks, immersion in 0.07% (700 ppm) or 0.1% (1,000 ppm) PAA for 10, 20, or 30 s achieved significant reductions ($P < 0.05$) in counts of *Salmonella* (for 0.07%, 1.7, 1.7, 1.7 log CFU/mL rinsate; for 0.1%, 1.5, 1.6, 1.7 log CFU/mL rinsate) and *Campylobacter* (for 0.07%, 3.4, 1.9, 2.2 log CFU/mL rinsate; for 0.1%, 2.4, 1.8, 2.3 log CFU/mL rinsate) *(61)*. Chlorine (0.003%, 30 ppm) for 10, 20, or 30 s also achieved significant reductions ($P < 0.05$) compared with initial counts (*Salmonella,* 0.7, 0.5, 0.4 log CFU/mL rinsate; *Campylobacter,* 0.7, 0.5, 0.6 log CFU/mL rinsate); however, reductions were similar to those achieved with immersion in water (*Salmonella,* 1 log CFU/mL rinsate on average, *Campylobacter,* 1 log CFU/mL rinsate on average). Zhang et al. *(62)* sprayed 3 mL of PAA (0.2%, 2,000 ppm) or chlorine (0.005%, 50 ppm) onto chicken skin samples inoculated with *Salmonella*. Reduction rates achieved by chlorine on loosely attached *Salmonella* bacteria (45, 56, 42, and 69%, depending on scald type) were much lower than those achieved by PAA (97, 96, 94, and 95%).

The effect of PAA- and chlorine-based interventions has been investigated in further processed poultry products. Chen et al. *(10)* used 0.003% (30 ppm) chlorine, 0.07% (700 ppm) PAA, and 0.1% (1,000 ppm) PAA to treat chicken parts by immersion for 23 s. The parts were then ground and sampled for *Salmonella* and *Campylobacter*. The PAA treatment had the greatest reduction on *Salmonella* (1.5 log CFU/g) and *Campylobacter* (1.3 log CFU/g) counts in the ground product, whereas the chlorine treatment was not different ($P > 0.05$) from the control water treatment. APC and psychrotrophic bacteria counts were also significantly lower for ground chicken treated with PAA compared with chlorine and continued to be lower during 7 days of storage. Zhang et al. *(60)* repeated the experiment with assorted chicken parts (breasts, drumsticks, thighs, and wings) and found similar reductions. After decontamination by immersion for 23 s, PAA at both concentrations achieved a 1.5-log CFU/mL rinsate reduction for *Campylobacter* and *Salmonella,* whereas chlorine provided <1-log CFU/mL rinsate reduction for both pathogens, similar to that achieved by a water rinse alone. Park et al. *(37)* also prepared ground chicken, by combining chicken breast with chicken skin inoculated with *Campylobacter, Listeria,* and *Salmonella* and treating both parts with PAA or chlorine before grinding. Parts were immersed for 16 s in 50 ppm of chlorine or 0.12% (1,200 ppm) PAA. After treatment with PAA, *Campylobacter, Listeria,* and *Salmonella* counts on ground chicken were 3.5, 4.3, and 4.4 log CFU/g, respectively, all of them significantly lower ($P < 0.05$) than counts obtained after chlorine treatment (5.0, 5.0, and 5.9 log CFU/g, respectively). Sukumaran et al. *(50)* treated chicken skin with PAA (50 ppm), PAA (400 ppm), or chlorine (30 ppm) for 20 s and found a significant difference ($P < 0.05$) between *Salmonella* counts for the chlorine treatment (2.8 log CFU/cm^2) and those for the 400-ppm PAA treatment (1.7 log CFU/cm^2). Moore et al. *(31)* treated inoculated chicken frames with 0.1% PAA (1,000 ppm) or sodium hypochlorite 0.005% (50 ppm) by dipping for 10 s in each antimicrobial solution. Frames were blended to obtain a sample similar to mechanically separated chicken and were tested for the inoculated *Salmonella* Heidelberg and *C. jejuni*. PAA significantly reduced *Salmonella* counts by 0.9 log CFU/g, whereas chlorine achieved a nonsignificant 0.4-log reduction. *Campylobacter* reductions were not significant for either treatment; however, counts with PAA were 0.7 log CFU/g lower than those of the control, whereas chlorine achieved only a 0.1-log reduction.

These studies suggest that a concentration of at least 400 ppm of PAA is more effective than chlorine for postchill reduction of *Salmonella* and *Campylobacter* in chicken parts and chicken skin. The decontamination effect of PAA is maintained as the parts are subjected to further

TABLE 1. *Comparison of PAA treatment to chlorine-based antimicrobial treatments for decontamination of raw poultry products*[a]

Step/product	Treatment	Quantitative reduction	Alternative treatment	Quantitative reduction	Reference
Prechill tank interventions: immersion					
Chicken carcass	PAA, 50 ppm, 25 min	APC: 0.5	ASC, 50 ppm, 25 min	APC: 0.4	*20*
	PAA, 50 ppm, 25 min	APC: 0.5	CD, 5 ppm, 25 min	APC: 0.2	*20*
	PAA, 200 ppm, 20 min	S: 0.3, C: 2.1,[b] TVC: 0.1	ASC, 900 ppm, 20 s, 4°C	S: 0.2, C: 2.0,[b] TVC: 1.5	*11*
Prechill tank interventions: spray					
Chicken carcass	PAA, 400 ppm, 30 s	C: 1.2	ASC, 1,000 ppm, 30 s	C: 1.3[b]	*40*
	PAA, 400 ppm, 30 s	C: 1.2	CD, 6 ppm, 30 s	C: 0.1	*40*
Postchill tank interventions: immersion					
Chicken skin	PAA, 220 ppm, 15 min	APC: 0.3	ASC, 1,200 ppm, 15 min	APC: 2.0[b]	*12*

[a] S, *Salmonella* counts; C, *Campylobacter* counts; TVC, total viable counts; APC, aerobic plate counts; PAA, peroxyacetic acid; ASC, acidified sodium chloride; CD, chlorine dioxide.
[b] Reduction was significantly different from the control, $P < 0.05$.

processing and has proved to be useful to improve the safety of ground poultry products.

Other chlorine-based compounds have been proposed for decontamination of poultry parts. These include ASC and CD. ASC aims to combine the antimicrobial action of both sodium chloride and organic acids, such as CA. The lower pH is expected to increase the effectiveness of chlorine because a pH lower than 7.0 to 7.5 is needed to ensure the presence of hypochlorous acid *(7)*. Chousalkar et al. *(11)* found that dipping chicken carcasses in ASC (900 ppm, 20 s) significantly reduced ($P < 0.05$) *Campylobacter* counts by 2.0 log CFU/cm^2 of carcass, whereas a PAA treatment (200 ppm, 20 min) achieved significant reductions ($P < 0.05$) of 2.1 log CFU/cm^2 of carcass. Initial *Campylobacter* counts were 2.2 and 2.5 log CFU/cm^2 of carcass for carcasses treated with ASC or PAA, respectively. ASC was also effective when applied as a spray (1,000 ppm, 30 s), significantly reducing ($P < 0.01$) *Campylobacter* counts by 1.3 log CFU/g on chicken breast skin. PAA (400 ppm, 30 s) reductions were not significantly different (1.2 log CFU/g) *(40)*. Additionally, del Río et al. *(12)* used ASC (1,200 ppm, 15 min), CA (2%, 15 min), TSP (12%, 15 min), and PAA (220 ppm, 15 min) as an immersion intervention on chicken skin. ASC and CA treatments achieved significant reductions ($P < 0.05$) of APC (2.0, 1.2, and 1.7 log CFU/g skin, respectively), whereas PAA reductions were not significant (0.3 log CFU/g skin). CD is a powerful oxidant that can damage fatty acids in the cell membrane, causing leakage of cellular contents; it can also damage microbial cellular proteins *(49)*. Its mode of action is similar to chlorine; however, unlike chlorine, CD does not react with natural organic materials to form potentially harmful disinfection by-products *(35)*. Table 1 presents a comparison between these interventions and PAA. In the studies found, these interventions were not more effective than PAA application.

PAA COMPARED WITH LA

LA has been used for the reduction of *Salmonella* on poultry products in the United States since the USDA-FSIS approved its use in 1994 *(26)*. Weak organic acids lower the intracellular pH of bacteria, causing damage to the outer or cytoplasmic membrane, thus resulting in bacterial inactivation *(22)*. Advantages of these compounds include high solubility and lack of accumulation in organisms or in the environment *(22)*. However, organic acids may cause discoloration at concentrations higher than 3% and off-flavors when used at or above 1%.

For poultry carcasses, meat, parts, trim, and giblets, a LA solution with a concentration of up to 5% may be used as a postchill intervention *(54)*. Commercial LA solutions can contain 80 to 88% (w/w) LA and must be stored in a cool and dry location for a shelf life of up to 3 years from the production date *(4, 23)*. Lemonakis et al. *(26)* compared a 5% LA solution to 0.1% (1,000 ppm) PAA for decontamination of chicken carcasses by immersion for 30 s. Significantly ($P < 0.05$) lower final counts were achieved with PAA for APC (4.3 log CFU/mL), *Salmonella* (3.9 log CFU/mL), and *E. faecium* (3.7 log CFU/mL) compared with LA (APC, 5.1 log CFU/mL; *Salmonella,* 4.3 log CFU/mL; and *E. faecium,* 4.8 log CFU/mL). Similar results were obtained when treating chicken wings, except for *Salmonella* counts, which were the same for both treatments. The authors concluded that LA may be more effective in applications with longer dipping times *(26)*. The experiment was repeated with the same sanitizer concentrations and treatment conditions using chicken wings inoculated with *C. jejuni (44)*. Survival counts for PAA (2.3 log CFU/g) and for LA (2.4 log CFU/g) were similar and were significantly lower ($P < 0.05$) than the initial counts (4.7 log CFU/g). A similar result was obtained when LA was compared with PAA for use in decontamination of ground chicken frames *(31)*. After a 10-s dipping time, LA (1.5%) and PAA (0.1%) were effective at reducing *Salmonella* by 0.5 and 0.9 log CFU/g, respectively. However, only the PAA treatment was significantly different from the control. Neither treatment was able to significantly reduce *C. jejuni* counts in the product on the day of application, but both treatments resulted in significantly lower counts ($P < 0.05$) of *C. jejuni* after 24 h of storage. This supports the notion that PAA may be

more effective at instant kill, whereas LA may exert a higher delayed antimicrobial potential.

The results are less conclusive when comparing LA and PAA in spraying systems. Purevdorj-Gage et al. *(39)* used a spray system to treat chicken breasts with PAA (50, 200, and 450 ppm) and LA (1, 3, and 5%) solutions. PAA treatments reduced *Salmonella* by numbers (0.95, 1.04, and 1.11 log, respectively) similar to those achieved by LA treatments (0.54, 0.8, and 1.15 log, respectively). In contrast, Ramirez-Hernandez et al. *(41)* tested a variety of commercially available organic acids: LA at 2.84 and 5.11%, LA plus acetic acid blend at 2.0 and 2.5%, buffered LA spray at 3.25 and 5.85%, and PAA at 200 and 400 ppm. Chicken thighs, with or without skin, were inoculated with *Salmonella* and then treated for 15 s in a commercial spray cabinet. Recovery of *Salmonella* was significantly lower for the 5.1% LA and the 5.85% buffered LA treatments compared with the control, for both skin-on and skin-off samples, whereas there was no difference between PAA treatments and the control. The experiment was repeated with chicken breasts, and no significant difference ($P < 0.01$) was found between LA (5.11%) and PAA (800 ppm) treatments and the water control. The *Salmonella* reductions for all treatments, including water, were about 0.5 log CFU/mL of chicken rinsate, which is lower than those reported by Purevdorj-Gage et al. *(39)* for similar antimicrobial concentrations. Only one primary study was found that compared the effect of spray treatments on *Campylobacter*. Shen et al. *(44)* used an electrostatic sprayer for 30 s to deliver either PAA (0.1%, 1,000 ppm) or LA (5%) to chicken wings inoculated with *C. jejuni* and found that both PAA and LA significantly reduced counts from 4.7 log CFU/g to 2.1 and 2.3 log CFU/g, respectively.

In conclusion, PAA is generally more effective than LA in the reported immersion studies, although the difference can be of little practical significance under certain exposure times and depending upon the target microorganism. There is not enough information to compare both chemicals as spray interventions. However, LA continues to be an attractive postchill treatment due to its nature as an organic acid and due to fewer occupational concerns compared to PAA.

PAA COMPARED WITH CPC

CPC has been reported to be the main postchill antimicrobial agent for drench cabinets in the poultry industry, but it can also be applied as a spray or immersion treatment *(10)*. It is a water-soluble, nonvolatile, quaternary ammonium compound *(31)*. CPC may be used as a spray of aqueous solution at concentrations that do not exceed 0.3 g of CPC per pound of raw poultry, or as an immersion solution with a concentration equal to or less than 0.8% CPC by weight *(54)*. Commercial solutions contain approximately 40% of CPC and must be diluted with potable tap water for use in poultry processing *(42)*. CPC solutions must also contain propylene glycol at a concentration of 1.5 times that of CPC because this helps stabilize the CPC in solution and reduces the absorption of CPC into the treated poultry tissues *(55)*. CPC integrates into the lipid membrane of bacterial cells, interfering with osmoregulation and homeostasis, leading to disintegration of membranes and leakage of cytoplasmic contents *(27)*. Regulations require CPC treatment to be followed by a water rinse of the product and require at least 99% of the antimicrobial to be collected and recycled; therefore, most CPC is collected and not released into the environment *(42)*.

CPC has been reported to inhibit and reverse the attachment of *Salmonella* to chicken skin *(50)*. Chen et al. *(10)* found that CPC treatment (23-s immersion) at either 0.35 or 0.6% achieved a 0.8-log CFU/g reduction of *Salmonella* and *Campylobacter* in ground chicken, which was significantly different from the reduction achieved by PAA (1.5 and 1.3 log CFU/g, respectively) or by water alone (0.5 log CFU/g). Moore et al. *(31)* compared the effect of 0.5% CPC and 0.1% PAA on *Salmonella* Heidelberg and *C. jejuni* counts in ground chicken frames dipped for 10 s in each antimicrobial. PAA was more effective than CPC on the day of application, with a *Salmonella* reduction of 0.9 log CFU/g and *Campylobacter* reduction of 0.7 log CFU/g, compared with CPC reductions of 0.5 and 0.4 log CFU/g for *Salmonella* and *Campylobacter,* respectively. However, after storage of the product for 24 h under refrigeration, both PAA and CPC treatments showed significantly lower counts of *Salmonella* compared with the control. Further research is needed to characterize microbial reduction counts over the shelf life of the product.

Scott et al. *(43)* treated *Salmonella*-inoculated chicken wings with either PAA (700 ppm, 20-s immersion) or CPC (4,000 ppm, 10-s immersion), and both treatments achieved a significant reduction in counts, although PAA (1.5-log CFU/mL rinsate reduction) was more effective than CPC (0.7-log CFU/mL rinsate reduction). In chicken drumsticks, PAA (0.07 and 0.1% for 10-, 20-, or 30-s immersion) achieved average reductions of 1.65 and 2.33 log CFU/mL rinsate of *Salmonella* and *Campylobacter,* respectively, whereas average CPC (0.35 and 0.6% for 10-, 20-, or 30-s immersion) reductions were 3.8 and 3.0 log CFU/mL rinsate, respectively *(61)*. In chicken skin, Sukumaran et al. *(50)* found that PAA (400 ppm, 20-s immersion) reduced *Salmonella* counts by 1.7 log CFU/cm^2, whereas CPC (0.2%, 20-s immersion) achieved a smaller reduction of 0.7 log CFU/cm^2. However, another study that used inoculated chicken parts found that PAA (0.1%, 23-s immersion) provided a reduction of 1.5 log CFU per sample of *Salmonella* and *Campylobacter,* whereas CPC (0.6%, 23-s immersion) was more effective, with *Salmonella* and *Campylobacter* reductions of 3.5 and 5.0 log CFU per sample, respectively *(60)*. Due to the variety of treatment concentrations and food matrixes, it is difficult to conclude whether PAA and CPC have a similar effectiveness for treatment of chicken parts. Importantly, no studies comparing spray application of PAA and CPC were found. Compared with PAA, the use of CPC requires additional equipment to recapture the chemical in processing water and to apply water rinses for poultry that has been treated *(60)*. This is due to the presence of propylene glycol in CPC solutions. Neither CPC nor propylene glycol residues are dangerous for humans; however, poultry parts may be used for cat food, and residual propylene glycol is a concern for these pets *(55)*. Therefore, implementation and use of PAA

in the poultry industry may be more practical than that of CPC.

ADBAC compounds, also known as benzalkonium chloride compounds, are a class of quaternary ammonium compounds, usually commercialized as a mixture of compounds with alkyl chains of different lengths *(28)*. The alkyl chains of benzalkonium chloride compounds perturb the bacterial membrane bilayer, whereas the charged nitrogen disrupts the charge distribution of the membrane *(28)*. ADBAC was compared with PAA in one study as a prechill tank intervention for chicken carcasses; however, ADBAC did not achieve significant reductions of APC, as shown in Table 2 *(20)*.

PAA COMPARED WITH OTHER INTERVENTIONS

A wide range of antimicrobials has been proposed for poultry decontamination. Among them, the following have been compared with PAA in published primary research studies (Table 2): TSP, CA, LCA, ALA, propionic acid, LAE, lysozyme, 1,3-dibromo-5,5-dimethylhydantoin, SSS (Amplon), PAA + T-128 chlorine stabilizer, ozone, Poultry-pHresh, hydrogen peroxide, and NEW. The practical use of antimicrobial treatments is limited due to potentially dangerous chemical residues, adverse effects on chicken quality, corrosiveness to equipment, cost considerations, and limited effectiveness, as well as due to occupational and environmental health concerns *(24)*. The studies comparing these interventions to PAA are limited, and more data are needed to reach reliable conclusions about effectiveness.

For prechill applications, only TSP was at least as effective as PAA. Purnell et al. *(40)* found that a TSP spray (12%, 30 s) achieved a significant reduction ($P < 0.01$) in *Campylobacter* counts of 1.4 log CFU/g on chicken breast skin, whereas PAA (400 ppm, 30 s) reductions were not significantly different (1.2 log CFU/g). TSP solutions at 12% are highly alkaline (pH 10 to 12) and have surfactant properties that prevent bacterial cells from attaching to the carcass *(7)*.

For postchill applications, SSS, LCA, and LAE interventions were similarly effective to PAA at reducing microbial counts. SSS (pH 1.4, 15 s) achieved a significant reduction ($P < 0.05$) of *Campylobacter* (1.5 log CFU per chicken) on chicken carcasses, whereas *Campylobacter* reductions were also significant ($P < 0.05$, 2.2 CFU per chicken) when using PAA (750 ppm, 15 s). However, SSS did not reduce APC, whereas PAA achieved significant reductions ($P < 0.05$, 4.1 log CFU per chicken) *(24)*. Scott et al. *(43)* found that SSS (pH 1.1, 20 s) immersion was effective for significantly reducing ($P < 0.05$) *Salmonella* (1.2 log CFU/mL rinsate) and APC (1.1 log CFU/mL rinsate) in chicken wings. PAA (700 ppm, 20 s) achieved similar significant reductions (*Salmonella,* 1.5 log CFU/mL rinsate; APC, 1.5 log CFU/mL rinsate). Additionally, Olson et al. *(36)* tested SSS (500 ppm) and PAA (500 ppm) as an immersion treatment (30 s) on turkey drumsticks and achieved significant reductions ($P < 0.0001$) in *Salmonella* counts with both treatments (PAA, 2.6 log CFU/g; SSS, 2.2 log CFU/g). SSS is an inorganic acid mixture, which has similar antimicrobial properties to organic acids. *Salmonella* is capable of developing acid tolerance after exposure to organic acids, such as those used in poultry operations. Inorganic acid mixtures such as SSS bypass this resistance, which makes them an attractive alternative *(36)*. Lemonakis et al. *(26)* used immersion in LCA (2.5%, 30 s) to significantly reduce *Salmonella* (1.1 log CFU/mL rinsate) and APC (0.7 log CFU/mL rinsate) on chicken carcasses, whereas immersion in PAA (1,000 ppm, 30 s) also achieved significant reductions of *Salmonella* (1.7 log CFU/mL rinsate) and APC (1.7 log CFU/mL rinsate). Shen et al. *(44)* also obtained significant reductions ($P < 0.05$) of *Campylobacter* (1.9 log CFU/g) when immersing chicken wings with LCA (2.5%, 30 s), although reductions with PAA (1,000 ppm, 30 s) were also significant compared with the control ($P < 0.05$, 2.3 log CFU/g). Used as an electrostatic spray, LCA (2.5%, 30 s) was slightly more effective than PAA (1,000 ppm, 30 s), with significant ($P < 0.05$) *Campylobacter* reductions of 2.4 and 2.1 log CFU/g, respectively. LCA is a buffered mix of LA and CA, and has been marketed as an alternative to chlorine for small poultry producers *(26)*. Lastly, Moore et al. *(31)* immersed chicken frames in both LAE (0.1%, 10 s) and PAA (1,000 ppm, 10 s). *Campylobacter* and APC numbers were not reduced significantly, but *Salmonella* bacteria were reduced by 0.9 log CFU/g in both treatments ($P < 0.05$). LAE is a cationic surfactant that acts as a broad spectrum antimicrobial because it can alter the cytoplasmic cell membranes *(31)*.

Some interventions were more effective than PAA, but only for chicken skin. del Rio et al. *(12)* used ASC (1,200 ppm, 15 min), CA (2%, 15 min), TSP (12%, 15 min), and PAA (220 ppm, 15 min) as an immersion intervention on chicken skin. ASC and CA treatments achieved significant reductions ($P < 0.05$) of APC (2.0, 1.2, and 1.7 log CFU/g of skin, respectively), whereas PAA reductions were not significant (0.3 log CFU/g skin).

An interesting trend is the combination of PAA and a second antimicrobial agent to improve PAA effectiveness, to reduce occupational exposures, and to reduce potential environmental impact. Steininger et al. *(48)* combined PAA (20 ppm) with T-128 stabilizer (0.5%) for a 15-min prechill whole carcass immersion treatment. The addition of T-128 stabilizer resulted in significant APC reductions ($P < 0.05$) of 1.2 log CFU/mL rinsate, compared to nonsignificant reductions with PAA alone (0.9 log CFU/mL rinsate). T-128 is a chemical blend of orthophosphoric acid and propylene glycol that helps stabilize chlorine and PAA *(48)*. Dittoe et al. *(14)* added ozone (10 ppm) to a PAA (500 ppm, 20 s) spray intervention for whole hen carcasses. Both PAA alone and PAA plus ozone reduced counts of *Salmonella, E. coli,* and *Campylobacter,* and the addition of ozone reduced ambient PAA significantly ($P < 0.001$, 0.565 to 0.052 ppm), which could increase employee safety *(14)*. Moghassem Hamidi et al. *(30)* immersed chicken breasts for 10 min in either PAA (400 ppm), NEW (200 ppm), or a mixture of PAA (200 ppm) and NEW (100 ppm). APC reductions were significant ($P < 0.05$) for the three treatments, and PAA+NEW reductions (1.2 log CFU/g of chicken meat) were higher than those for PAA or NEW alone (1.1 and 1.0 log CFU/g of chicken meat, respectively). NEW is prepared by passing a diluted sodium chloride solution through an electrochemical cell, generating a

TABLE 2. *Comparison of PAA treatment to other antimicrobial chemical treatments for decontamination of raw poultry products*

Step/product	Treatment	Quantitative reduction	Alternative treatment	Quantitative reduction	Reference
Prechill tank interventions: immersion					
Chicken carcass	PAA, 50 ppm, 25 min	APC: 0.5	ASC, 50 ppm, 25 min	APC: 0.4	*20*
	PAA, 50 ppm, 25 min	APC: 0.5	ADBAC, 175 ppm, 25 min	APC: 0.5	*20*
	PAA, 50 ppm, 25 min	APC: 0.5	CD, 5 ppm, 25 min	APC: 0.2	*20*
	PAA, 20 ppm, 15 min	APC: 0.9	PAA, 20 ppm + T-128 stabilizer, 0.5%, 15 min	APC: 1.2[b]	*48*
	PAA, 200 ppm, 20 min	S: 0.3, C: 2.1,[b] TVC: 0.1	ASC, 900 ppm, 20 s, 4°C	S: 0.2, C: 2.0,[b] TVC: 1.5	*11*
	PAA, 200 ppm, 20 min	S: 0.3, C: 2.1,[b] TVC: 0.1	PoultrypHresh, pH 1.4–1.6, 12 s, 4°C	S: 0.2, C: 0.7,[b] TVC: 0.2	*11*
Prechill tank interventions: spray					
Chicken carcass	PAA, 400 ppm, 30 s	C: 1.2	ASC, 1,000 ppm, 30 s	C: 1.3[b]	*40*
	PAA, 400 ppm, 30 s	C: 1.2	CD, 6 ppm, 30 s	C: 0.1	*40*
	PAA, 400 ppm, 30 s	C: 1.2	TSP, 12%, 30 s	C: 1.4[b]	*40*
	PAA, 500 ppm, 20 s	S: 0.1, EC: 0.6,[b] C: 0.4[b]	Ozone, 10 ppm, 20 s	S: 0.1, EC: 0.2, C: 0.2	*14*
	PAA, 500 ppm, 20 s	S: 0.1, EC: 0.6,[b] C: 0.4[b]	PAA, 500 ppm + ozone, 10 ppm, 20 s	S: 0.4, EC: 0.4, C: 0.3[b]	*14*
Chill tank interventions					
Chicken carcass	PAA, 5,000 ppm, 45 min	S (%): 5.0[b]	Ozone, 125 mg/L, 45 min	S (%): 15.0	*56*
	PAA, 5,000 ppm, 45 min	S (%): 5.0[b]	Hydrogen peroxide, 30 mg/L, 45 min	S (%): 16.0	*56*
Postchill tank interventions: immersion					
Chicken carcass	PAA, 750 ppm, 15 s	S (%): 0.0, C: 2.2,[b] APC: 4.1[b]	SSS, pH 1.4, 15 s	S (%): 20.0, C: 1.5,[b] APC: 0.0	*24*
	PAA, 1,000 ppm, 30 s	S: 1.7,[b] APC: 1.7[b]	LCA, 2.5%, 30 s	S: 1.1,[b] APC: 0.7[b]	*26*
	PAA, 1,000 ppm, 20 s	S: 2.1,[b] C: 2.0[b]	Lysozyme, 5,000 ppm, 20 s	0.9,[b] C: 0.9[b]	*32*
Chicken wings	PAA, 1,000 ppm, 30 s	S: 1.3,[b] APC: 1.4[b]	LCA, 2.5%, 30 s	S: 1.0,[b] APC: 0.6[b]	*26*
	PAA, 700 ppm, 20 s	S: 1.5,[b] APC: 1.5[b]	SSS, pH 1.1, 20 s	S: 1.2,[b] APC: 1.1[b]	*43*
	PAA, 1,000 ppm, 30 s	C: 2.3[b]	LCA, 2.5%, 30 s	C: 1.9[b]	*44*
	PAA, 1,000 ppm, 30 s	C: 2.3[b]	Sani-Date, 0.25%, 30 s	C: 1.5[b]	*44*
Chicken breast	PAA, 400 ppm, 10 min	APC: 1.1[b]	NEW, 200 ppm, 10 min	APC: 1.0[b]	*30*
	PAA, 400 ppm, 10 min	APC: 1.1[b]	PAA, 200 ppm + NEW, 100 ppm, 10 min	APC: 1.2[b]	*30*
Turkey drumstick	PAA, 500 ppm, 30 s	S: 2.6[b]	SSS, 500 ppm, pH 1.3, 30 s	S: 2.2[b]	*36*
	PAA, 500 ppm, 30 s	S: 2.6[b]	PAA, 500 ppm + SSS, 500 ppm, 30 s	S: 2.8[b]	*36*
Chicken skin	PAA, 400 ppm, 20 s	S: 1.7[b]	LAE, 200 ppm, 20 s	S: 0.6[b]	*50*
	PAA, 220 ppm, 15 min	APC: 0.3	ASC, 1,200 ppm, 15 min	APC: 2.0[b]	*12*
	PAA, 220 ppm, 15 min	APC: 0.3	CA, 2%, 15 min	APC: 1.2[b]	*12*
	PAA, 220 ppm, 15 min	APC: 0.3	TSP, 12%, 15 min	APC: 1.7[b]	*12*
Ground chicken	PAA, 1,000 ppm, 10 s	S: 0.9,[b] C: 0.7, APC: 0.2	ALA, 1.5%, 10 s	S: 0.5, C: 1.0, APC: 0.0	*31*
	PAA, 1,000 ppm, 10 s	S: 0.9,[b] C: 0.7, APC: 0.2	LAE, 0.1%, 10 s	S: 0.9,[b] C: 1.1, APC: NA	*31*
	PAA, 1,000 ppm, 10 s	S: 0.9,[b] C: 0.7, APC: 0.2	Propionic acid, 0.3%, 10 s	S: 0.5, C: 1.2, APC: 0.0	*31*
Postchill tank interventions: spray					
Chicken breast	PAA, 450 ppm	S: 1.1	DBDMH, 450 ppm	S: 0.8	*39*
Chicken wings	PAA, 1,000 ppm, 30 s	C: 2.1[b]	LCA, 2.5%, 30 s	C: 2.4[b]	*44*
	PAA, 1,000 ppm, 30 s	C: 2.1[b]	Sani-Date, 0.25%, 30 s	C: 2.4[b]	*44*
Chicken skin, dry scalded	PAA, 2,000 ppm, 3 mL	S (%): 99	PAA, 2,000 ppm + SDS, 0.5%, 3 mL	S (%): 97	*62*
Chicken skin, rinsed	PAA, 2,000 ppm, 3 mL	S (%): 94	PAA, 2,000 ppm + SDS, 0.5%, 3 mL	S (%): 96	*62*
Chicken skin, soft scalded	PAA, 2,000 ppm, 3 mL	S (%): 94	PAA, 2,000 ppm + SDS, 0.5%, 3 mL	S (%): 94	*62*

TABLE 2. *Continued*

Step/product	Treatment	Quantitative reduction	Alternative treatment	Quantitative reduction	Reference
Chicken skin, hard scalded	PAA, 2,000 ppm, 3 mL	S (%): 96	PAA, 2,000 ppm + SDS, 0.5%, 3 mL	S (%): 95	*62*

[a] S, *Salmonella* counts; S (%), *Salmonella* prevalence; C, *Campylobacter* counts; EC, *E. coli* counts; TVC, total viable counts; APC, aerobic plate counts; NA, not available; PAA, peroxyacetic acid; ADBAC, alkyl dimethyl benzyl ammonium chloride; ALA, acidified lactic acid; CA, citric acid; DBDMH, 1,3-dibromo-5,5-dimethylhydantoin; LAE, lauric alginate; LCA, lactic and citric acid blend; NEW, near-neutral electrolyzed water; SDS, sodium dodecyl sulfate; SSS, sodium sulfate and sulfuric acid blend (Amplon); TSP, trisodium phosphate; Sani-Date, PAA and hydrogen peroxide mix.
[b] Reduction was significantly different from the control, $P < 0.05$.

solution with an almost neutral pH that contains hypochlorous acid, hypochlorite ions, and trace amounts of chlorine *(30)*. Olson et al. *(36)* compared PAA (500 ppm) to a combination of PAA (500 ppm) plus SSS (500 ppm) on turkey drumsticks inoculated with *Salmonella*. The reductions were significant ($P < 0.0001$) for both treatments and were slightly higher for PAA+SSS (2.8 log CFU/g) than for PAA alone (2.6 log CFU/g). As discussed previously, the addition of SSS contributes to inactivate *Salmonella* cells that have acquired acid resistance to organic acids *(36)*. Finally, Zhang et al. *(62)* spray treated chicken skin samples with either PAA (2,000 ppm, 3 mL) or PAA (2,000 ppm) plus SDS (0.5%, 3 mL) to reduce *Salmonella* counts. SDS is an anionic surfactant, with potential to lower surface tension and to improve antimicrobial activity. However, it did not increase the antimicrobial efficacy of PAA under the studied conditions. More studies on these hurdle approaches are necessary to reach solid conclusions and apply the results to industry.

CONCLUSIONS

PAA as an antimicrobial intervention for poultry processing has been compared with at least 20 different antimicrobial compounds in the published literature, and the most popular comparisons are to chlorine compounds, LA, and CPC. PAA is consistently more effective than chlorine at reducing *Salmonella* and *Campylobacter* counts and prevalence, whereas results are less conclusive for CPC and LA. Spray application of antimicrobials shows more variable results than immersion methods. More research is needed to be able to reach conclusions about TSP, LAE, and ASC for a range of products and treatment conditions. Some researchers have proposed combining PAA with other antimicrobial compounds to increase its effectiveness and, possibly, reduce its occupational hazards, with some initially promising results *(14)*. The growing body of science-based evidence will be useful to continue to reduce the burden of foodborne illness associated with the consumption of contaminated poultry products.

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