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Review

Electrolyzed Water and Its Application in the Food Industry

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ABSTRACT

Electrolyzed water (EW) is gaining popularity as a sanitizer in the food industries of many countries. By electrolysis, a dilute sodium chloride solution dissociates into acidic electrolyzed water (AEW), which has a pH of 2 to 3, an oxidation-reduction potential of >1,100 mV, and an active chlorine content of 10 to 90 ppm, and basic electrolyzed water (BEW), which has a pH of 10 to 13 and an oxidation-reduction potential of −800 to −900 mV. Vegetative cells of various bacteria in suspension were generally reduced by >6.0 log CFU/ml when AEW was used. However, AEW is a less effective bactericide on utensils, surfaces, and food products because of factors such as surface type and the presence of organic matter. Reductions of bacteria on surfaces and utensils or vegetables and fruits mainly ranged from about 2.0 to 6.0 or 1.0 to 3.5 orders of magnitude, respectively. Higher reductions were obtained for tomatoes. For chicken carcasses, pork, and fish, reductions ranged from about 0.8 to 3.0, 1.0 to 1.8, and 0.4 to 2.8 orders of magnitude, respectively. Considerable reductions were achieved with AEW on eggs. On some food commodities, treatment with BEW followed by AEW produced higher reductions than did treatment with AEW only. EW technology deserves consideration when discussing industrial sanitization of equipment and decontamination of food products. Nevertheless, decontamination treatments for food products always should be considered part of an integral food safety system. Such treatments cannot replace strict adherence to good manufacturing and hygiene practices.

Cleaning and sanitizing are important elements of the hygiene practices in a food processing plant. Typical sanitizers applied in the food industry include chlorine compounds, organic acids, trisodium phosphate, iodophores, and quaternary ammonium compounds. Chlorine compounds are often the most effective, although they may be more corrosive and irritating than alternatives such as iodine and quaternary ammonium compounds. Chemical substances also are used for decontamination of certain food products. In the United States, decontamination treatments with certain antimicrobials have been authorized for carcasses, but such treatments are not permitted at present in the European Union. Some of these procedures have been found unacceptable because of chemical residues, high cost, limited effectiveness, or discoloration of products.

Currently, electrolyzed water (EW) is gaining popularity as a sanitizer in the food industry to reduce or eliminate bacterial populations on food products, food-processing surfaces, and non–food contact surfaces. In Japan, the Health, Labor and Welfare Ministry has approved EW as a food additive *(110).* EW generators also have been approved for use in the food industry by the U.S. Environmental Protection Agency *(88).* The purpose of this review is to provide an overview of issues related to EW, its antimicrobial activity, and its application in the food industry.

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CONCEPT OF EW

History. The concept of EW was originally developed in Russia, where it has been used for water decontamination, water regeneration, and disinfection in medical institutions *(58, 59, 77, 78).* Since the 1980s, EW also has been used in Japan. One of the first applications of EW was the sterilization of medical instruments in hospitals *(60, 98).* Later, it was utilized in various fields such as agriculture or livestock management *(4, 17, 99),* but the use of EW has been restricted by its short shelf life. With recent improvements in technology and the availability of better equipment, EW has gained popularity as a disinfectant in the food industry.

Generation. EW is the product of the electrolysis of a dilute NaCl or KCl-$MgCl_2$ solution in an electrolysis cell, within which a diaphragm (septum or membrane) separates the anode and cathode. The basic approach for producing EW is shown in Figure 1. The voltage between the electrodes is generally set at 9 to 10 V *(5).* During electrolysis, NaCl dissolved in deionized water dissociates into negatively charged chlorine (Cl^-) and positively charged sodium (Na^+). At the same time, hydroxide (OH^-) and hydrogen (H^+) ions are formed. Negatively charged ions such as Cl^- and OH^- move to the anode to give up electrons and become oxygen gas (O_2), chlorine gas (Cl_2), hypochlorite ion (OCl^-), hypochlorous acid (HOCl), and hydrochloric acid, and positively charged ions such as H^+ and Na^+ move to the cathode to take up electrons and become hydrogen gas (H_2) and sodium hydroxide (NaOH). The solution dissoci-

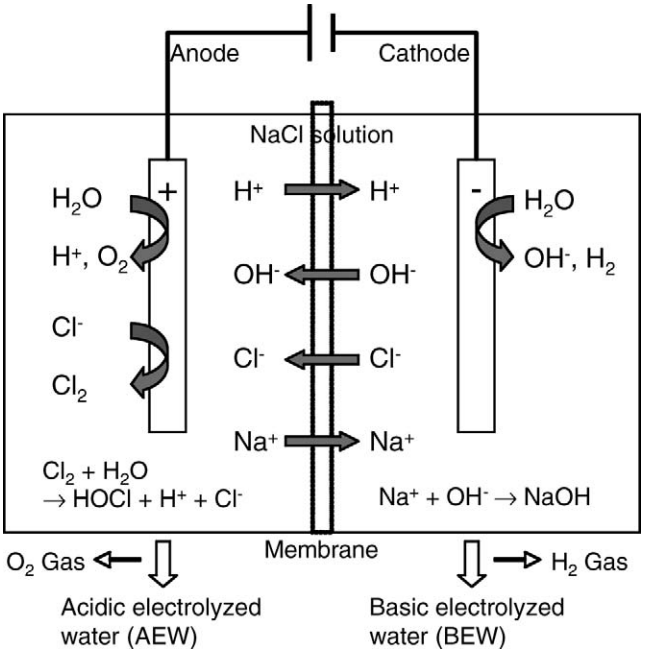

FIGURE 1. *Schematic of electrolyzed water generation. The basic chemical reactions at the anode can be summarized as follows:* $2H_2O \rightarrow 4H^+ + O_2\uparrow + 4e^-$, $2NaCl \rightarrow Cl_2\uparrow + 2e^- + 2Na^+$, *and* $Cl_2 + H_2O \rightarrow HCl + HOCl$. *At the cathode, the main chemical reactions are* $2H_2O + 2e^- \rightarrow 2OH^- + H_2\uparrow$ *and* $2NaCl + 2OH^- \rightarrow 2NaOH + Cl^-$.

ates into an acidic solution from the anode, with a pH of 2 to 3, an oxidation-reduction potential (ORP) of >1,100 mV, and an active chlorine content (ACC) of 10 to 90 ppm, and a basic solution from the cathode, with a pH of 10 to 13 and an ORP of −800 to −900 mV. The solution from the anode is called acidic electrolyzed water (AEW), acid oxidizing water, or electrolyzed oxidizing water, and the cathodic solution is known as basic electrolyzed water (BEW), alkaline electrolyzed water, or electrolyzed reducing water. Neutral electrolyzed water (NEW), with a pH of 7 to 8 and an ORP of 750 mV, is produced by mixing the anodic solution with OH^- ions or by using a single-cell chamber *(5, 21, 22, 39, 109).*

Various EW-producing machines are available in the market. Japan is currently the principal manufacturer of such machines *(5).* Generally, machines can be divided into those that contain a diaphragm and produce AEW and BEW (two-cell chamber) and those that do not contain a diaphragm and therefore produce NEW (single-cell chamber). The physical properties and chemical composition of EW vary depending on the concentration of NaCl, amperage level, time of electrolysis, or water flow rate *(47).* Based on their control systems, machines allow the users to select (i) the brine flow rate, (ii) the amperages and/or voltages, or (iii) a preset chlorine concentration.

General application. AEW has strong antimicrobial activity against a variety of microorganisms. It may have a wide range of applications such as medicine (e.g., treatment of wounds or disinfection of medical equipment and surfaces), dentistry, agriculture, livestock management, aquaculture, and food industries. BEW is mostly used as cleanser and degreaser before treatment with disinfecting agents *(7, 15, 27, 52, 57).* BEW also has a strong reducing potential that is responsible for the reduction of free radicals *(5).* In some applications, pretreatment with BEW followed by treatment with AEW was more effective than AEW treatment only. Pretreatment with BEW seems to sensitize bacterial cell surfaces to the disinfecting agent. NEW is used less frequently than is AEW but has the advantage of being less corrosive and having a longer shelf life *(21, 76).* Hence, NEW may be an alternative to AEW under certain circumstances *(22, 39, 109).*

Antimicrobial activity of AEW. It is not clear whether pH, chlorine compounds, ORP, or combinations of these factors are responsible for the antimicrobial activity of AEW. The presence of chlorine and a high ORP seem to be the main contributors to the antimicrobial activity of AEW *(5).*

The low pH of AEW is believed to reduce bacterial growth and make the bacterial cells more sensitive to active chlorine by sensitizing their outer membrane to the entry of HOCl *(87).* Active chlorine compounds can destroy the membranes of microorganisms, but other modes of chlorine action (e.g., decarboxylation of amino acids, reactions with nucleic acids, and unbalanced metabolism after the destruction of key enzymes) also have been proposed *(47, 53, 71, 72).* Studies suggest that HOCl is the most active of the chlorine compounds *(55, 71, 72).* HOCl penetrates cell membranes and produces hydroxyl radicals, which exert their antimicrobial activity through the oxidation of key metabolic systems. The relative fractions of chlorine compounds (Cl_2, HOCl, and OCl^-) are pH dependent and affect the bactericidal activity of AEW *(25, 41, 63, 72, 87).* The highest proportion of HOCl and maximal efficiency of AEW for inactivating bacteria was found at a pH of about 4.0 to 5.0. More Cl_2 was present at lower pH values, and more OCl^- was present at higher pH values. The bactericidal activity of AEW and ORP increase with active chlorine concentrations, indicating that chlorine is a strong oxidizing agent *(87).* Complete inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* was reported at ACCs of 2 ppm or higher, regardless of pH *(87).*

Some authors have suggested that the high ORP is the determining factor for the antimicrobial activity of AEW *(4, 41, 65, 106).* Al-Haq et al. *(5)* reported that inactivation of *E. coli* was primarily dependent on ORP and not on residual chlorine. The ORP of a solution is an indicator of its ability to oxidize or reduce, with higher ORP values corresponding to greater oxidizing strength. The high ORP of AEW may be due to the oxygen released by the rupture of the weak and unstable bond between the hydroxy and chloric radicals *(5).* The high ORP probably changes the electron flow in the cells. Oxidation due to the high ORP of AEW may damage cell membranes, cause the oxidation of sulfhydryl compounds on cell surfaces, and create disruption in cell metabolic processes, leading to the inactivation of bacterial cells *(64, 65).* Basically, the high ORP and low pH of AEW seem to act synergistically with HOCl to inactivate microorganisms *(11, 65, 87, 88).* Besides,

complete loss of bactericidal activity was observed when ORP decreased to less than 848 mV *(99).*

Factors influencing the antimicrobial activity of AEW. A limiting factor for the use of AEW is its loss of activity over time due to chlorine loss and ensuing HOCl decomposition *(53, 62).* When stored under open conditions, AEW rapidly loses its residual chlorine because of to Cl_2 evaporation *(5).* Len et al. *(62)* observed a total chlorine loss within 100 h of storage. Under closed conditions, chlorine loss is due to self-decomposition, which is slower than the evaporation loss under open conditions. Chlorine loss by decomposition can be enhanced by exposure to diffused light and agitation *(62).* The ratio of Cl_2 among chlorine compounds is pH dependent *(63, 87).* The lower the pH, the more Cl_2 exists in the solution, and this Cl_2 can easily volatilize. Theoretically, almost no chlorine loss occurs at a pH of 9 *(62).*

Temperature, agitation, and contact with organic compounds also influence the antimicrobial activity of AEW. At higher temperatures, cell membranes of gram-negative bacteria become more fluid, and AEW enters the cells more rapidly *(7, 24).* Low storage temperatures seem to stabilize residual chlorine and ORP *(24).* When AEW treatment was combined with agitation, higher microbial reductions were observed *(88).* Cells removed from the surfaces during agitation probably were immediately inactivated by AEW *(5, 88).* Agitation also might have facilitated the penetration of AEW into the remaining cell layers, or the well-mixed AEW may have allowed chlorine to react with cells more efficiently. However, the presence of organic matter reduced ACCs and ORPs rapidly *(8, 82).* Chlorine compounds react with proteins to form organochloramines, which have a much weaker antimicrobial activity than does free chlorine.

Advantages and disadvantages of AEW. AEW is environment friendly because it is generated by electrolysis of only water and a dilute salt solution *(41, 50, 88).* After use, AEW reverts to normal water *(5, 13).* Hence, there is no need for special handling, storage, or transportation of concentrated chemicals that are a potential health hazard *(5).* Because of its nonselective antimicrobial properties, AEW does not promote the development of bacterial resistance *(5, 108).* The use of AEW on various food commodities (e.g., produce and fish) did not negatively affect the organoleptic properties of color, scent, flavor, or texture *(2, 5, 33, 34, 43, 48, 71).* Many types of EW-producing machines allow EW to be produced on site, and operational costs are low because only salt is needed to generate the sanitizing solution *(5, 13).*

Despite the listed advantages, some disadvantages associated with the application of AEW must be considered: (i) the initial costs for the purchase of the equipment may be high *(5)*; (ii) some machines may form chlorine gas and cause discomfort for the operator *(3, 4)*; (iii) AEW might be corrosive, irritating for hands, and phytotoxic because of its high ORP or free chlorine content *(31, 62, 76, 94)*; and (iv) antimicrobial activity may be reduced by the presence of organic matter or as a result of inappropriate storage *(8, 13, 54, 82, 95).*

ANTIMICROBIAL ACTIVITY OF EW AGAINST MICROORGANISMS IN SUSPENSION

The antimicrobial activity of AEW and NEW against various microorganisms is shown in Table 1. Generally, reductions of >6.0 log CFU/ml were reported for a variety of bacteria. The effectiveness of EW for reducing microorganisms is influenced by several factors such as type of EW, ACC, exposure time, treatment temperature, pH, and amperage or voltage. Because conditions differ among studies, comparison of the results is often hampered. Fenner et al. *(28)* found marked differences in sensitivity to AEW among different bacterial species; *Proteus mirabilis* and *Staphylococcus aureus* were more sensitive to AEW than were *Mycobacterium avium* subsp. *avium, Pseudomonas aeruginosa,* and *Enterococcus faecium.*

To be considered effective, a sanitizer applied for 0.5 min must reduce microbial populations in suspension or in a biofilm by at least 5 or 3 orders of magnitude, respectively *(8, 12, 21, 66, 75, 97, 105).* When AEW and NEW were used against suspended vegetative bacterial cells, these criteria were met in most instances (Table 1). Spores, especially those of *Bacillus,* required longer exposure times than do vegetative cells to obtain reductions of >5.0 log CFU/ml *(40, 108).*

Venkitanarayanan et al. *(106)* found that exposure to AEW reduced *E. coli* O157:H7 by >8.0 log CFU/ml within 5 min. At higher temperatures (35 and 45°C), *E. coli* O157:H7 was inactivated at comparable levels after a shorter exposure time. Compared with the results of other studies, the relatively high ACC is noteworthy (Table 1). Venkitanarayanan et al. *(106)* also reported that AEW treatment reduced *Salmonella* Enteritidis from 7.8 log CFU/ml to nondetectable levels within 10 min and to less than 1.0 log CFU/ml within 5 min. For *Campylobacter jejuni* and various *Vibrio* species, AEW exposure of a few seconds yielded reductions of >6.5 log CFU/ml *(86, 90).* When NEW was used for 5 min (ACCs ranging from 60 to 93 ppm), *E. coli* O157:H7 was reduced from 7.5 log CFU/ml to nondetectable levels and *Salmonella* Enteritidis was reduced by >6.0 log CFU/ml *(20, 21).*

Similar to the inactivation of *E. coli* O157:H7 and *Salmonella* Enteritidis, reductions of *L. monocytogenes* by >7.0 log CFU/ml were observed by Venkitanarayanan et al. *(106)* after the application of AEW (Table 1). When AEW with a slightly increased ACC was used, *L. monocytogenes* was reduced by 9.2 log CFU/ml within a few seconds *(40),* and NEW (ACC of 60 ppm) yielded reductions of >7.0 log CFU/ml within 5 min *(20, 21).*

S. aureus is involved in a wide variety of infections, and some strains producing staphylococcal enterotoxins are responsible for foodborne intoxications. Park et al. *(88)* observed reductions of *S. aureus* by >9.0 log CFU/ml within 0.5 min (Table 1). Decreasing the ACC to 10 ppm yielded reductions of only 4.0 log CFU/ml. Fenner et al. *(28)* reported a reduction of *S. aureus* populations (8.0 log CFU/ml) to nondetectable levels within 5 min, whereas Vorobjeva et al. *(108)* obtained the same reductions within 0.5 min. When NEW with increased ACC was used, *S. aureus*

TABLE 1. *Antimicrobial activity of AEW and NEW against microorganisms in suspension*

Microorganism	EW type	Reduction (log CFU ml^{-1})	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference
Aeromonas liquefaciens	AEW	>7.0	NA[a]	0.5	2.8	1,125	43	*108*
Alcaligenes faecalis	AEW	>7.0	NA	0.5	2.8	1,125	43	*108*
Bacillus spp.	AEW	2.3	25	1	2.2	NA	40	*72*
B. cereus	AEW	8.0	24	0.5	2.5	1,123	10	*40*
Spores	AEW	3.5	24	2	2.5	1,123	10	*40*
Cells and spores	AEW	>6.0	NA	5	2.8	1,125	43	*108*
B. subtilis	AEW	>6.0	NA	5	2.2	1,153	49	*47*
Campylobacter jejuni	AEW	>7.0	23	0.2	2.6	1,082	50	*86*
Citrobacter freundii	AEW	>7.0	NA	0.5	2.8	1,125	43	*108*
Enterobacter aerogenes	AEW	>9.0	23	0.5	2.8	1,163	25	*88*
Enterobacteriaceae	AEW	>6.0	NA	1	2.2	NA	40	*72*
Enterococcus faecium	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
	AEW	8.0	22	15	3.0	1,100	40	*28*
	NEW	>6.0	25	10	6.5	850	20	*32*
Escherichia coli	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
	NEW	>6.0	23	5	8.2	745	93	*20*
	NEW	>6.0	25	10	6.5	850	20	*32*
E. coli O157:H7	AEW	8.9	24	0.2	2.6	1,160	56	*40*
	AEW	>8.0	23	5	2.4	1,155	82	*106*
	AEW	8.0	35	2	2.4	1,155	82	*106*
	AEW	8.0	45	1	2.4	1,155	82	*106*
	AEW	>7.0	22	1	2.5	1,130	45	*84*
	NEW	>7.0	23	5	8.0	>700	60	*21*
Flavobacter spp.	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
	AEW	>6.0	NA	1	2.2	NA	40	*72*
Listeria monocytogenes	AEW	9.2	24	0.2	2.6	1,160	56	*40*
	AEW	>8.0	23	0.1	2.5	1,150	50	*67*
	AEW	>7.0	22	1	2.5	1,130	45	*84*
	AEW	>7.0	4	10	2.6	1,158	48	*106*
	AEW	>7.0	23	5	2.6	1,158	48	*106*
	AEW	>7.0	35	2	2.6	1,158	48	*106*
	AEW	>7.0	45	1	2.6	1,158	48	*106*
	AEW	>6.0	NA	1	2.4	1,170	44	*8*
	NEW	>7.0	23	5	8.0	>700	60	*21*
	NEW	>6.0	25	10	6.5	850	20	*32*
Mycobacterium avium subsp. *avium*	AEW	8.0	22	15	3.0	1,100	40	*28*
Proteus mirabilis	AEW	8.0	22	5	3.0	1,100	40	*28*
P. vulgaris	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
Pseudomonas aeruginosa	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
	AEW	8.0	22	30	3	1,100	40	*28*
	AEW	>6.0	NA	5	2.2	1,153	49	*47*
	NEW	>7.0	23	5	8.0	>700	60	*21*
Salmonella Enteritidis	AEW	>7.0	23	5	2.4	1,151	82	*106*
	NEW	>6.0	23	5	8.2	745	93	*20*
Salmonella Typhimurium	NEW	>6.0	25	10	6.5	850	20	*32*
Staphylococcus aureus	AEW	>9.0	23	0.5	2.8	1,163	25	*88*
	AEW	>8.0	NA	0.5	2.8	1,125	43	*108*
	AEW	8.0	22	5	3.0	1,100	40	*28*
	AEW	4.1	23	0.5	3.2	1,116	10	*86*
	NEW	>7.0	23	5	8.0	>700	60	*21*
	NEW	>6.0	25	10	6.5	850	20	*32*
Vibrio parahaemolyticus	AEW	>6.6	NA	0.3	3.2	1,104	10	*90*
V. vulnificus	AEW	>6.6	NA	0.3	3.2	1,104	10	*90*
Aspergillus parasiticus spores	AEW	3.0	NA	15	2.5	1,164	20–30	*103*
Candida albicans	AEW	8.0	22	5	3.0	1,100	40	*28*
Penicillium expansum spores	AEW	4.0	NA	5	3.5	1,027	18	*79*
	AEW	4.8	NA	0.5	3.1	1,133	60	*80*

[a] NA, not available.

was reduced by >7.0 log CFU/ml within 5 min *(21).* The results reported by Suzuki et al. *(102)* suggest that AEW is able to inactivate the staphylococcal enterotoxin A by cleaving it into peptide fragments.

Spores are generally less sensitive than vegetative cells to disinfecting agents, including AEW (Table 1). To reduce *Bacillus cereus* spores by 3.5 orders of magnitude, an exposure time of 2 min was required, whereas vegetative cells were reduced by 8.0 log CFU/ml within 0.5 min *(40).* However, when AEW containing 43 ppm of active chlorine was used for 5 min, reductions of more than 6 orders of magnitude were noted for both vegetative cells and spores *(108).* Otherwise, an exposure time of 15 min was required to inactivate an initial count of 1,000 *Aspergillus parasiticus* spores by AEW containing 20 to 30 ppm of active chlorine *(103).* The results also suggest that AEW might be able to eliminate the mutagenicity of aflatoxin B_1 through the action of hydroxyl radicals originating from HOCl.

Researchers also confirmed that AEW is effective against bloodborne viruses, including hepatitis B virus, hepatitis C virus, and human immunodeficiency virus *(46, 74, 93, 104).* In view of foodborne viral infections, additional investigations are needed to evaluate the use of AEW against viruses in food.

ANTIMICROBIAL ACTIVITY OF EW AGAINST MICROORGANISMS ON SURFACES AND UTENSILS

Surfaces and utensils are important sources of direct or indirect contamination of food products with pathogenic and spoilage microorganisms. ACCs and the antimicrobial activity of AEW is reduced in proportion to the amount of organic residue present on these surfaces *(8, 82).* Ayebah et al. *(8)* recommended sequential treatment with BEW and AEW. BEW should remove food residues and make the adherent bacteria more susceptible to AEW. Besides, AEW seems to be effective for preventing cross-contamination *(37, 38, 43, 57, 88).*

Cutting boards. Venkitanarayanan et al. *(107)* examined the efficiency of AEW at different temperatures and ACCs for inactivating *E. coli* O157:H7 and *L. monocytogenes* on plastic cutting boards. The highest reductions were obtained for *E. coli* O157:H7 at 35°C for 20 min, 45°C for 10 min, or 55°C for 5 min and for *L. monocytogenes* at 35°C for 10 min (Table 2). *Vibrio parahaemolyticus* was reduced from 5.8 to less than 1.0 log CFU/cm^2 after 1 min of exposure to AEW *(18).* By rinsing plastic cutting boards with NEW, *E. coli, S. aureus, P. aeruginosa,* and *L. monocytogenes* were reduced by about 5 orders of magnitude *(22).*

Wooden cutting boards are considered more difficult to sanitize than plastic boards *(1, 18).* Because of its physical structure, wood is able to absorb moisture and protect bacteria from disinfecting agents. However, certain wood species have endogenous antibacterial properties, resulting in the desiccation of bacteria as a result of hygroscopic characteristics. Rinsing wooden cutting boards with NEW for 1 min reduced populations of *E. coli, S. aureus, P. aeruginosa,* and *L. monocytogenes* by less than 3 orders of magnitude *(22).* Extending the exposure time to 5 min yielded reductions of about 4 orders of magnitude (Table 2). No significant differences were found between the application of AEW and distilled water in inactivating *V. parahaemolyticus* on bamboo cutting boards *(18).* Bamboo may contain substances that interact with chlorine-based compounds and neutralize the antibacterial activity.

Processing gloves. Liu and Su *(68)* analyzed the effects of AEW on reusable and disposable gloves (natural rubber latex, natural latex, and nitrile) and on clean and soiled gloves. *L. monocytogenes* was completely inactivated on each glove type after 5 min of treatment (Table 2). Longer survival of *L. monocytogenes* was observed in the presence of organic matter (Table 3).

Stainless steel, tiles, glass, and vitreous china. On stainless steel, application of AEW for 5 min yielded reductions of 1.8 to 3.7 orders of magnitude (Table 2). Populations of *V. parahaemolyticus* were reduced by more than 5.0 log CFU/cm^2 within only 0.5 min *(18).* In the presence of organic matter (crab meat residues), *L. monocytogenes* was reduced by 2.3 orders of magnitude (Table 3). When NEW was used for 1 min, *E. coli* O157:H7, *L. monocytogenes, P. aeruginosa,* and *S. aureus* were reduced by more than 6 orders of magnitude (Table 2). High reductions were also obtained for these pathogens on glass *(21).*

On tiles, application of AEW for 5 min yielded reductions of 1.8 to 4.2 orders of magnitude (Table 2). Populations of *V. parahaemolyticus* were reduced by more than 5.0 log CFU/cm^2 within less than 1 min *(18).* In the presence of organic matter, *L. monocytogenes* was reduced by 1.5 to 2.3 orders of magnitude (Table 3). Results from vitreous china were comparable with those from stainless steel, tiles, or glass (Table 2). With agitation, *Enterobacter aerogenes* and *S. aureus* were reduced to nondetectable levels (3.0 log CFU/cm^2) on vitreous china *(88).*

Biofilms. Biofilms are a structured community of bacterial cells enclosed in a self-producing polymer matrix (glycocalyx), which is a protected mode of growth on surfaces and allows survival in hostile environments. The higher resistance of bacteria in biofilms to sanitizers has been attributed to various factors such as protection by the matrix, neutralization of the sanitizer, genetic modification of the cell wall, and slow uptake of antimicrobial agents *(16, 19, 23, 100).* Only limited data exist on the efficiency of EW for inactivating bacteria in biofilms.

Kim et al. *(42)* found that AEW reduced *L. monocytogenes* in biofilms on stainless steel to nondetectable levels within 5 min (Table 2). The highest inactivation rate was reported within the first seconds of treatment. Thus, AEW needed longer exposure times to reach the cells inside the biofilm. Ayebah et al. *(7)* reported reductions of *L. monocytogenes* by 4.3 to 5.2 orders of magnitude, depending on the treatment time. The effectiveness of AEW solutions with different ACCs (47 and 85 ppm) did not differ significantly. In other studies, the existence of a threshold concentration of chlorine also has been suggested; beyond this threshold, further increases in concentration do not enhance

TABLE 2. *Antimicrobial activity of AEW and NEW on surfaces and utensils*

Material, surface	Microorganisms	EW type	Reduction (log CFU)	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference(s)
Ceramic tile	Aerobic bacteria	AEW	2.4/cm^2	NA[a]	1	2.6	1,156	55	*37, 38*
	Enterobacter aerogenes	AEW	2.2/cm^2	23	5	2.6	1,181	53	*88*
	Staphylococcus aureus	AEW	1.8/cm^2	23	5	2.6	1,181	53	*88*
	Vibrio parahaemolyticus	AEW	>5.0/cm^2	NA	0.8	2.7	1,151	40	*18*
Ceramic tile chips	*Listeria monocytogenes*	AEW	4.2/25 cm^2	NA	5	2.5	1,150	50	*67*
Cutting boards									
Bamboo	*V. parahaemolyticus*	AEW	3.5/cm^2	NA	5	2.7	1,151	40	*18*
Plastic	*Escherichia coli*	NEW	5.0/50 cm^2	NA	1	7.8	775	64	*22*
	E. coli O157:H7	AEW	8.0/100 cm^2	35	20	2.6	1,162	90	*107*
		AEW	8.0/100 cm^2	45	10	2.5	1,157	93	*107*
		AEW	8.0/100 cm^2	55	5	2.3	1,147	45	*107*
	L. monocytogenes	NEW	5.0/50 cm^2	NA	1	7.8	775	64	*22*
		AEW	5.3/100 cm^2	35	10	2.4	1,156	66	*107*
	Pseudomonas aeruginosa	NEW	5.0/50 cm^2	NA	1	7.8	775	64	*22*
	S. aureus	NEW	5.0/50 cm^2	NA	1	7.8	775	64	*22*
	V. parahaemolyticus	AEW	>5.0/cm^2	NA	1	2.7	1,151	40	*18*
Wood	*E. coli*	NEW	4.0/50 cm^2	NA	5	7.8	775	64	*22*
	L. monocytogenes	NEW	4.0/50 cm^2	NA	5	7.8	775	64	*22*
	P. aeruginosa	NEW	4.0/50 cm^2	NA	5	7.8	775	64	*22*
	S. aureus	NEW	4.0/50 cm^2	NA	5	7.8	775	64	*22*
	V. parahaemolyticus	AEW	5.7/cm^2	NA	5	2.7	1,151	40	*18*
Glass	*E. aerogenes*	AEW	2.2/cm^2	23	5	2.6	1,181	53	*88*
	E. coli O157:H7	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	L. monocytogenes	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	P. aeruginosa	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	S. aureus	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
		AEW	1.7/cm^2	23	5	2.6	1,181	53	*88*
Gloves	*L. monocytogenes*	AEW	4.5 to 5.5/cm^2	23	5	2.6	1,125	40	*68*
Stainless steel	*E. aerogenes*	AEW	2.4/cm^2	23	5	2.6	1,181	53	*88*
	E. coli O157:H7	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	L. monocytogenes	AEW	3.7/25 cm^2	NA	5	2.5	1,150	50	*67*
		NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	L. monocytogenes								
	Biofilms	AEW	4.3/10 cm^2	24	0.5	2.4	1,163	47	*7*
	Biofilms	AEW	5.2/10 cm^2	24	2	2.4	1,163	47	*7*
	Biofilms	AEW	5.8/83 cm^2	23	0.2	2.6	1,160	56	*42*
	Biofilms	AEW	>10/83 cm^2	23	5	2.6	1,160	56	*42*
	P. aeruginosa	NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	S. aureus	AEW	1.8/cm^2	23	5	2.6	1,181	53	*88*
		NEW	>6.0/50 cm^2	23	1	8.0	>700	60	*21*
	V. parahaemolyticus	AEW	>5.0/cm^2	NA	0.5	2.7	1,151	40	*18*
Vitreous china	*E. aerogenes*	AEW	2.3/cm^2	23	5	2.6	1,181	53	*88*
	S. aureus	AEW	1.9/cm^2	23	5	2.6	1,181	53	*88*

[a] NA, not available.

TABLE 3. *Antimicrobial activity of AEW against* Listeria monocytogenes *in the presence of organic matter or food residues*

Material	Reduction (log CFU)	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference
Ceramic tiles with crab meat residues	2.3/25 cm^2	NA[a]	5	2.5	1,150	50	*67*
Floor tiles with crab meat residues	1.5/25 cm^2	NA	5	2.5	1,150	50	*67*
Processing gloves with cooked shrimp meat diluted with distilled water	1.6–3.8/16 cm^2	24	5	2.6	1,125	40	*68*
Stainless steel (biofilm), chicken serum added to the treatment solution							
5 ml/liter	2.7/10 cm^2	24	0.5	2.3	1,166	44	*8*
7.5 ml/liter	2.0/10 cm^2	24	0.5	2.3	1,166	44	*8*
	>4.0/10 cm^2	24	1	2.3	1,166	44	*8*
Stainless steel with crab meat residues	2.3/25 cm^2	NA	5	2.5	1,150	50	*67*

[a] NA, not available.

the effectiveness *(61, 91).* The reductions of *L. monocytogenes* in biofilms obtained in the presence of organic matter are shown in Table 3. Moreover, Ayebah et al. *(7)* obtained the highest reductions with sequential BEW and AEW treatment, even in the presence of organic matter. The higher efficiency of this sequential treatment was also reported by Koseki et al. *(55, 57).* BEW probably destabilized or dissolved the glycocalyx and thus facilitated the penetration of the active AEW components.

Abattoirs. Bach et al. *(9)* compared the effectiveness of AEW and a common sanitizer (Mikrolene) for the use in abattoirs. After standard precleaning, AEW was more effective for inactivating bacteria in various slaughterhouse areas. During the slaughter of cattle, the contamination risk associated with the hide is of special concern. Both saprophytes and pathogens such as *E. coli* O157:H7 can be transferred to the carcass during dehiding *(6, 70, 73, 89).* In addition to the maintenance and optimization of slaughter hygiene practices, decontamination treatments for hides have been established *(10, 49, 96).* Bosilevac et al. *(15)* used a high-pressure spray treatment of BEW (52°C for 10 s at pH 11.2) and AEW (60°C for 10 s at pH 2.4 and an ACC of 70 ppm) on cattle hides. The results were comparable to those obtained with other hide treatments; total microbial counts and *Enterobacteriaceae* counts were reduced by 3.5 and 4.3 log CFU/100 cm^2, respectively. However, the effect of this specific treatment was smaller in a previous study *(14).*

ANTIMICROBIAL ACTIVITY OF EW AGAINST MICROORGANISMS IN PROCESSING WATER

Water washing is widely used for produce and minimally processed vegetables, and accumulation of microorganisms in the processing water must be prevented *(29).* Ongeng et al. *(81)* investigated the effect of the electrolysis procedure on water used for the washing of vegetables, and the antimicrobial activity against *Pseudomonas fluorescens, Pantoea agglomerans,* and *Rahnella aquatilis* was tested. Industrial processing water, which had a higher microbial load (8.0 log CFU/ml) and organic load than did tap water, had a microbial load of >6.0 log CFU/ml after electrolysis with the attainable amperage of 0.7 A (ACC of 1.1 ppm). When salt was added to the water (5 ml of 20% NaCl per 10 liters), the tested bacteria were reduced by about 4 orders of magnitude. By raising the amperage to 1.3 A, which generated ACCs above 2 ppm, complete inactivation was achieved. AEW produced with tap water had stronger antimicrobial activity than did AEW produced with processing water *(81).*

ANTIMICROBIAL ACTIVITY OF EW AGAINST MICROORGANISMS ON FOOD PRODUCTS

The antimicrobial activities of AEW or NEW on various food products are shown in Tables 4 and 5, and the effects of sequential BEW and AEW treatments are summarized in Table 6.

Vegetables and fruits. On strawberries, AEW treatment for 10 min achieved a reduction of naturally present aerobic bacteria, coliforms, and fungi by 1.6, 2.4, and 1.6 log CFU per strawberry, respectively, to nondetectable levels *(56).* Similar reductions also were obtained on cucumbers (Table 4). The combined treatment with BEW and AEW yielded higher reductions for cucumbers but not for strawberries (Table 6). The results for strawberries are in agreement with those of other studies *(56, 69, 112).* Longer exposure times were required for sanitizers to infiltrate the strawberry surface, probably because of the complex surface structure. On tomatoes, AEW reduced *E. coli* O157:H7, *L. monocytogenes,* and *Salmonella* Enteritidis by about 7.5 log CFU per tomato *(11).*

After application to lettuce of AEW containing only 3.6 ppm of active chlorine, Ongeng et al. *(81)* observed 2.6-, 1.9-, and 3.3-log reductions of *Enterobacteriaceae,* lactic acid bacteria, and psychrotrophs, respectively. Park et al. *(84)* reported similar reductions of *E. coli* O157:H7 (2.8 log CFU per leaf) and *L. monocytogenes* (2.4 log CFU per leaf) after AEW treatment (Table 4). AEW was as effective as chlorine for reducing *E. coli* O157:H7, *Salmonella,* and *L. monocytogenes* on leafy greens *(101).* Thus, AEW may be used as a suitable alternative to chlorine for the treatment of leafy greens.

In another study *(57),* the effects of temperature and BEW pretreatment on the efficiency of AEW against *E. coli*

TABLE 4. *Antimicrobial activity of AEW and NEW on fruits and vegetables*

Food product	Microorganisms	EW type	Reduction (log CFU)	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference
Carrots (slices)	Aerobic bacteria	NEW	1.0/g	23	3	6.8	NA[a]	20	*39*
Cucumbers	Aerobic bacteria	AEW	1.5/cucumber	NA	10	2.6	1,130	32.1	*56*
	Coliforms	AEW	1.7/cucumber	NA	10	2.6	1,130	32.1	*56*
	Fungi	AEW	1.7/cucumber	NA	10	2.6	1,130	32.1	*56*
Lettuce	Aerobic bacteria	AEW	2.0/g	NA	5	2.6	1,140	30	*55*
	Enterobacteriaceae	NA	2.6/g	NA	5	NA	NA	3.6	*81*
	Enterococcus faecalis	NEW	2.6/ml	25	10	6.5	850	50	*32*
	Escherichia coli	NEW	0.2/ml	25	10	6.5	850	50	*32*
	E. coli O157:H7	AEW	2.4/leaf	22	3	2.5	1,130	45	*84*
		NEW	3.0/g	30	5	7	>750	22–198	*109*
	E. coli O157:H7 and	AEW	0.6–0.9/g	4 or 20	1	2.6	NA	40	*57*
	Salmonella (Typhimu-	AEW	1.3–1.4/g	20	5	2.6	NA	40	*57*
	rium and Enteritidis)	AEW	2.7–3.0/g	50	1	2.6	NA	40	*57*
		AEW	4.0/g	50	5	2.6	NA	40	*57*
	Lactic acid bacteria	NA	1.9/g	NA	5	NA	NA	3.6	*81*
	Listeria monocytogenes	AEW	2.8/leaf	22	3	2.5	1,130	45	*84*
		NEW	4.0/g	30	5	7	>750	22–198	*109*
		NEW	2.5/ml	25	10	6.5	850	50	*32*
	Psychrotrophs	NA	3.3/g	NA	5	NA	NA	3.6	*81*
	Salmonella Typhimurium	NEW	2.5/g	30	5	7	>750	22–198	*109*
		NEW	2.9/ml	25	10	6.5	850	50	*32*
	Staphylococcus aureus	NEW	2.8/ml	25	10	6.5	850	50	*32*
Potatoes (diced)	Aerobic bacteria	NEW	0.1/g	23	4	6.8	NA	20	*39*
Radish (shreds)	Aerobic bacteria	NEW	0.5/g	23	3	6.8	NA	20	*39*
Spinach (leaves)	Aerobic bacteria	NEW	2.3/g	23	3	6.8	NA	20	*39*
	Enterococcus faecalis	NEW	3.5/ml	25	10	6.5	850	50	*32*
	E. coli	NEW	2.6/ml	25	10	6.5	850	50	*32*
	L. monocytogenes	NEW	>4.9/ml	25	10	6.5	850	50	*32*
	Salmonella Typhimurium	NEW	2.3/ml	25	10	6.5	850	50	*32*
	S. aureus	NEW	>4.3/ml	25	10	6.5	850	50	*32*
Strawberries	Aerobic bacteria	AEW	1.6/strawberry	NA	10	2.6	1,130	32.1	*56*
	Coliforms	AEW	2.4/strawberry	NA	10	2.6	1,130	32.1	*56*
	Fungi	AEW	1.6/strawberry	NA	10	2.6	1,130	32.1	*56*
Tomatoes	*E. coli*	NEW	5.0/cm^2	23	1	8.2	745	93	*20*
	E. coli O157:H7	AEW	7.6/tomato	23	NA	2.6	1,140	30	*11*
		NEW	4.9/cm^2	23	1	8.2	745	93	*20*
	L. monocytogenes	AEW	7.5/tomato	23	NA	2.6	1,140	30	*11*
		NEW	4.7/cm^2	23	1	8.2	745	93	*20*
	Salmonella Enteritidis	AEW	7.4/tomato	23	NA	2.6	1,140	30	*11*
		NEW	4.3/cm^2	23	1	8.2	745	93	*20*

[a] NA, not available.

O157:H7 and *Salmonella* on lettuce were examined (Table 4). Reductions obtained by AEW at 4°C or room temperature within 1 min were not higher than those obtained by chlorinated or distilled water. Higher temperature (50°C) and/or exposure time (5 min) yielded greater reductions. BEW pretreatment at room temperature for 5 min increased the reductions by about 0.5 order of magnitude (Table 6). The greatest reductions were obtained at a pretreatment temperature of 50°C regardless of duration or temperature of the AEW treatment *(57).* Yang et al. *(109)* examined the effects of BEW and AEW (30°C for 5 min at pH 9 or 4, an ORP of −750 or 1,150 mV, and an ACC of 22 to 198 ppm) on biofilms attached to lettuce leaves. *E. coli* O157:H7, *L. monocytogenes,* and *Salmonella* Typhimurium were reduced by about 2 orders of magnitude.

After treatment with NEW for 5 min, *E. coli* O157:H7, *L. monocytogenes,* and *Salmonella* Typhimurium on lettuce were reduced by 3.0, 4.0, and 2.5 log CFU/g, respectively *(109).* In another study, NEW reduced *L. monocytogenes* and *Salmonella* Enteritidis on tomatoes by 4.3 to 4.9 log CFU/cm^2 *(20).* NEW also reduced aerobic bacteria on diced potatoes, radish shreds, carrot slices, and spinach leaves by 0.1 to 2.3 log CFU/g (Table 4). Rinsing was thereby generally more effective than dipping *(39).*

Fish and seafood. On carp skin treated for 15 min with AEW, total microbial counts were reduced by 2.8 log CFU/cm^2 (Table 5). Pretreatment with BEW yielded comparable results (Table 6). On tilapia skin immersed in AEW, greater reductions were obtained for *V. parahaemolyticus* than for

TABLE 5. *Antimicrobial activity of AEW and NEW on various food products*

Product	Microorganisms	EW type	Reduction (log CFU)	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference
Fish and seafood									
Carp (skin)	Aerobic bacteria	AEW	2.8/cm^2	25	15	2.2	1,137	41	*72*
Carp (filets)	Aerobic bacteria	AEW	2.0/g	25	15	2.2	1,137	41	*72*
Oysters	*Vibrio parahaemolyticus*	AEW	1.1/g	NA[a]	240	2.8	1,131	30	*90*
	V. vulnificus	AEW	1.1/g	NA	240	2.8	1,131	30	*90*
Tilapia (skin)	*Escherichia coli* O157:H7	AEW	0.6–0.8/cm^2	23	1–10	2.5	1,159	120	*37*
	V. parahaemolyticus	AEW	2.6/cm^2	23	10	2.5	1,159	120	*37*
Tuna (filets)	Aerobic bacteria	AEW	1.0/g	NA	NA	NA	NA	50	*38*
	Aerobic bacteria	AEW	1.0/g	NA	NA	NA	NA	NA	*111*
Salmon (filets)	*E. coli* O157:H7	AEW	0.5/g	22	2	2.6	1,150	76–90	*83*
		AEW	1.1/g	35	64	2.6	1,150	76–90	*83*
	Listeria monocytogenes	AEW	0.4/g	22	2	2.6	1,150	76–90	*83*
Carcasses, raw meat, and ready-to-eat meat									
Chicken carcasses	Aerobic bacteria	AEW	1.3/ml of rinsate	4	45	2.6	1,150	50	*27*
	Campylobacter jejuni	AEW	2.3/g	NA	40	2.5	1,140	47	*44*
	Coliforms	AEW	1.1/ml of rinsate	4	45	2.6	1,150	50	*27*
	E. coli	AEW	1.1/ml of rinsate	4	45	2.6	1,150	50	*27*
	Salmonella Typhimurium	AEW	0.8/ml of rinsate	4	45	2.6	1,150	50	*27*
Chicken wings	*C. jejuni*	AEW	3.0/g	4 or 23	10 or 23	2.6	1,082	51.6	*86*
Frankfurters, ham	*L. monocytogenes*	AEW	<1.0/g	25	0.3	2.3	1,130	36	*26*
Frankfurters	*L. monocytogenes*	AEW	1.5/g	25	15	2.3	1,130	36	*26*
Pork	Aerobic bacteria	AEW	1.2/cm^2	NA	0.3	2.8	1,144	68	*25*
	Campylobacter coli	AEW	1.8/cm^2	NA	0.3	2.8	1,144	68	*25*
	Coliforms	AEW	1.2/cm^2	NA	0.3	2.8	1,144	68	*25*
	E. coli	AEW	1.1/cm^2	NA	0.3	2.8	1,144	68	*25*
	L. monocytogenes	AEW	1.2/cm^2	NA	0.3	2.8	1,144	68	*25*
	Salmonella Typhimurium	AEW	1.7/cm^2	NA	0.3	2.8	1,144	68	*25*
Shell eggs	*E. coli*	AEW	4–6/egg	NA	0.3 (hourly)	2.1	1,150	8	*92*
	L. monocytogenes	AEW	3.7/egg	NA	5	2.7	1,089	16	*85*
		AEW	1–4/egg	NA	0.3 (hourly)	2.1	1,150	8	*92*
	Salmonella Enteritidis	AEW	2.3/egg	NA	5	2.7	1,089	16	*85*
	Salmonella Typhimurium	AEW	4–6/egg	NA	0.3 (hourly)	2.1	1,150	8	*92*
	Staphylococcus aureus	AEW	3–6/egg	NA	0.3 (hourly)	2.1	1,150	8	*92*

[a] NA, not available.

TABLE 6. *Antimicrobial activity of sequential BEW and AEW treatment on various food products*

Product	Microorganism	Reduction (log CFU)	Temp (°C)	Exposure time (min)	pH	ORP (mV)	Active chlorine (ppm)	Reference
Chicken carcasses	Aerobic bacteria	2.4/ml of rinsate	BEW, NA[a]	NA	BEW, 11.6	BEW, −795	BEW, 0	*27*
	Coliforms	1.6/ml of rinsate	AEW, 4		AEW, 2.6	AEW, 1,150	AEW, 50	
	Escherichia coli	1.5/ml of rinsate						
	Salmonella Typhimurium	2.1/ml of rinsate						
Carp (skin)	Aerobic bacteria	2.6/cm^2	BEW, 25	BEW, 15	BEW, 11.6	BEW, −885	BEW, 0.9	*72*
			AEW, 25	AEW, 15	AEW, 2.2	AEW, 1,137	AEW, 41	
Cucumbers	Aerobic bacteria	2.0/cucumber	NA	BEW, 5	BEW, 11.3	BEW, −870	BEW, NA	*56*
	Coliforms	1.7/cucumber		AEW, 5	AEW, 2.6	AEW, 1,130	AEW, 32	
	Fungi	2.0/cucumber						
Frankfurters	*Listeria monocytogenes*	<1.0/g	BEW, 25	BEW, 0.3	BEW, NA	BEW, NA	BEW, NA	*26*
			AEW, 25	AEW, 0.3	AEW, 2.3	AEW, 1,130	AEW, 36	
Lettuce	Aerobic bacteria	2.0/g	NA	BEW, 1	BEW, 11.4	BEW, −870	BEW, NA	*55*
				AEW, 1	AEW, 2.6	AEW, 1,140	AEW, 30	
	E. coli O157:H7 and *Salmonella* (Typhimurium and Enteritidis)	1.8/g	BEW, 20	BEW, 5	BEW, 11.4	NA	BEW, 0	*57*
			AEW, 20	AEW, 5	AEW, 2.6		AEW, 40	
		2.7/g	BEW, 50	BEW, 1	BEW, 11.4	NA	BEW, 0	*57*
			AEW, 4	AEW, 1/5	AEW, 2.6		AEW, 40	
		4.0/g	BEW, 50	BEW, 5	BEW, 11.4	NA	BEW, 0	*57*
			AEW, 4	AEW, 1/5	AEW, 2.6	NA	AEW, 40	
Shell eggs	*Listeria monocytogenes*	3.0/egg	NA	BEW, 1	BEW, 11.2	BEW, −940	BEW, 0	*85*
	Salmonella Enteritidis	3.7/egg	NA	AEW, 1	AEW, 2.7	AEW, 1,089	AEW, 16	
Strawberries	Aerobic bacteria	1.0/strawberry	NA	BEW, 5	BEW, 11.3	BEW, −870	BEW, NA	*56*
	Coliforms	2.4/strawberry		AEW, 5	AEW, 2.6	AEW, 1,130	AEW, 32	
	Fungi	1.0/strawberry						

[a] NA, not available.

E. coli O157:H7 *(37).* On carp filets treated for 15 min with AEW, total microbial counts were reduced by 2.0 log CFU/g *(72).* AEW treatment of tuna filets yielded reductions of the natural microflora by about 1 order of magnitude (Table 5). Ozer and Demirci *(83)* reported reductions of *E. coli* O157:H7 and *L. monocytogenes* on salmon filets ranging from 0.4 to 1.1 log CFU/g, depending on exposure time and temperature.

To investigate the antimicrobial effect of AEW on oysters, inoculated oysters were placed into tanks containing AEW (ACC of 30 ppm), and the AEW salt concentration was set at 1% *(90).* After 4 h of exposure, *V. parahaemolyticus* and *Vibrio vulnificus* were reduced by about 1 order of magnitude (Table 5). Further exposure did not increase the reductions. Probably because of the unfavorable growth environment, oysters eventually stopped filtering water, thereby hampering the entry of AEW *(90).*

Carcasses, raw meat, and ready-to-eat meat. Fabrizio et al. *(27)* compared the effect of AEW solutions for immersion and spray washing of chicken carcasses. Immersion of carcasses in AEW (4°C for 45 min) reduced aerobic bacteria, total coliforms, *E. coli,* and *Salmonella* Typhimurium by 0.8 to 1.3 log CFU/ml of carcass rinsate (Table 5). Reductions obtained by spray washing (15 s) with AEW or distilled water did not differ significantly. Spray washing with BEW followed by immersion in AEW (Table 6) yielded greater reductions of 1.5 to 2.4 log CFU/ml. Spray treatment with BEW was as effective for removing fecal material as was the commonly used treatment with trisodium phosphate *(44).* Moreover, the results of Hinton et al. *(35)* suggested that AEW treatment extended the shelf life of refrigerated poultry.

Kim et al. *(44)* investigated the effectiveness of AEW for reducing *C. jejuni* on chicken carcasses (Table 5). Reductions of 2.3 log CFU/g were obtained by immersion, but additional prespraying did not improve the efficiency. Spray treatment alone reduced *C. jejuni* by 1.1 log CFU/g. However, all treatments failed to completely eliminate *Campylobacter.* On fresh chicken wings, AEW reduced *C. jejuni* by about 3 orders of magnitude and was therefore as effective as chlorine water *(86).* Gellynck et al. *(30)* analyzed the economics of reducing *Campylobacter* to different levels within the poultry meat chain (farm, processing plant, and consumer) and found that the decontamination of carcasses with AEW in the processing plant was the most efficient (cost-benefit ratio) of the evaluated measures.

Fabrizio and Cutter *(25)* investigated the effectiveness of AEW spray treatment on pork bellies for reducing total microbial counts and *Campylobacter coli,* coliform, *E. coli, L. monocytogenes,* and *Salmonella* Typhimurium counts (Table 5). Only the effect of AEW against *Campylobacter* differed significantly from that obtained with distilled water (1.8 log CFU/cm^2). On frankfurters and ham, spray treatment with AEW or a combined spray treatment with BEW and AEW failed to reduce *L. monocytogenes* by more than 1 order of magnitude (Tables 5 and 6). Other tested sanitizing agents also did not achieve greater reductions *(26)* perhaps because of the short contact times and the binding of chemicals by proteins. By dipping frankfurters in AEW for 15 min, *L. monocytogenes* was reduced by 1.5 log CFU/g (Table 5).

Eggs. Electrostatic spraying of shell eggs with AEW (hourly for 24 h) reduced *E. coli, S. aureus,* and *Salmonella* Typhimurium by 3 to 6 orders of magnitude (Table 5), whereas *L. monocytogenes* was reduced by 1.0 to 4.0 log CFU per egg *(92).* In another study, immersion of eggs in AEW for 5 min with agitation (100 rpm) reduced *L. monocytogenes* and *Salmonella* Enteritidis by 3.7 and 2.3 log CFU per egg, respectively *(85).* Prewash with BEW yielded reductions of ≥3.0 log CFU per egg after shorter exposure times (Table 6).

Application of AEW as ice. AEW may be applied as solution or ice. Frozen AEW was tested on lettuce and pacific saury *(45, 51).* The main antimicrobial effect of frozen AEW was attributed to the emitted Cl_2 *(36, 50).* Cl_2 emission in frozen AEW was proportional to the ACC before freezing *(51).* Because the boiling point of Cl_2 is −34°C, frozen AEW should be prepared at −40°C to prevent early chlorine loss.

On iceberg lettuce placed into containers with frozen AEW (pH 2.6), 1.5-log reductions of *L. monocytogenes* were observed, and no significant differences were found at ACCs of 40 and 70 ppm *(51).* The greatest reductions of *E. coli* O157:H7 (2.5 log CFU/g) were obtained with frozen AEW containing 240 ppm of active chlorine. However, this ACC caused an adverse effect resembling leaf burn. Frozen AEW with ACCs of 40 and 70 ppm did not affect the color of lettuce and still reduced *E. coli* O157:H7 by 1 order of magnitude. To achieve reductions of both pathogens by at least 1.5 log CFU/g, 10 times the weight of frozen AEW relative to the weight of the lettuce was required. The best results were obtained after an exposure time of 120 min. Longer exposure did not lead to further reductions. Frozen AEW may serve simultaneously for refrigeration and control of pathogens *(51).*

In another study, frozen AEW (pH 5.1 and ACC of 47 ppm) was used on pacific saury to extend shelf life, suppress lipid oxidation and the formation of volatile basic nitrogen, and retard the accumulation of alkaline compounds *(45).* In this study, the storage of saury in frozen tap water and frozen AEW were compared. The growth of aerobic bacteria and psychrotrophs was slower and growth of coliforms did not occur when saury was stored with frozen AEW.

IMPACT OF EW APPLICATION FOR THE FOOD INDUSTRY

AEW treatment may be used to inactivate foodborne pathogens and reduce microbial contamination on processing surfaces and various food products (e.g., vegetables and fruits). However, microbial reductions on surfaces and especially on food products were not as great as those obtained in suspension. In particular, the adverse effect of organic mater on the antimicrobial activity of AEW must be considered when this technology is used in the food industry.

On some food commodities, treatment with BEW followed by AEW resulted in greater antimicrobial activity than

that achieved by treatment with AEW only. Sequential BEW and AEW treatment also yielded the greatest reductions in *L. monocytogenes* biofilms on stainless steel, even in the presence of organic matter. Hence, the combination of AEW with other antimicrobial agents should be further evaluated.

The EW technology deserves consideration in discussions of sanitization of equipment or decontamination of certain food products. Nevertheless, decontamination treatments for food products always must be part of an integral food safety system. Such treatments cannot replace strict adherence to good manufacturing and hygiene practices at all stages of the food production process.

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