Comprehensive
REVIEWS
in Food Science and Food Safety

Electrolyzed Water as a Novel Sanitizer in the Food Industry: Current Trends and Future Perspectives

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Abstract: Electrolyzed water (EW) has gained immense popularity over the last few decades as a novel broad-spectrum sanitizer. EW can be produced using tap water with table salt as the singular chemical additive. The application of EW is a sustainable and green concept and has several advantages over traditional cleaning systems including cost effectiveness, ease of application, effective disinfection, on-the-spot production, and safety for human beings and the environment. These features make it an appropriate sanitizing and cleaning system for use in high-risk settings such as in hospitals and other healthcare facilities as well as in food processing environments. EW also has the potential for use in educational building, offices, and entertainment venues. However, there have been a number of issues related to the use of EW in various sectors including limited knowledge on the sanitizing mechanism. AEW, in particular, has shown limited efficacy on utensils, food products, and surfaces owing to various factors, the most important of which include the type of surface, presence of organic matter, and type of tape water used. The present review article highlights recent developments and offers new perspectives related to the use of EW in various areas, with particular focus on the food industry.

Keywords: decontamination techniques, electrolyzed water, foodborne pathogens, food safety

Practical Application: From an industrial viewpoint, this publication can be used for the comparison and improvement of electrolyzed water (EW) generators. From a scientific standpoint, this publication can help in understanding the role of various parameters and can provide insight into EW producing systems and its applications for further research and development.

Introduction

Center of disease control and prevention (CDC) has reported that there are 31 known foodborne pathogens or unspecified agents that cause infections in humans and has estimated that 48 million people become ill, 128000 are hospitalized, and 3000 die annually of foodborne diseases in the United States alone (CDC 2015). Therefore, developing effective sanitizers for killing pathogens in agricultural and food products is one of the most significant steps for the hazard analysis and critical control point (HACCP) system in the food industry (Issa-Zacharia and others 2010a). The food industry has employed a number of decontamination techniques throughout the food chain. However, some of these techniques possess disadvantages such as high cost, remaining chemical residues, low efficacy, and adverse effects on the quality of food products (Al-Haq and others 2005). A sanitizer can only be used in practice when it is not produced by the simple dilution of hazardous chemical solutions (Rahman and others 2010b).

Electrolyzed water (EW) has been regarded as a new sanitizer (EW containing HOCl) and cleaner (EW containing NaOH) in recent years. EW is produced from regular water without the addition of any harmful chemicals, except NaCl (Kim and others 2000a). The main reason for its popularity is the simplicity of production and application. The acceptance of EW as a sanitizer is evident from its use in a number of applications in various fields including agriculture, medical sterilization, food sanitation, livestock management, and other fields that employ antimicrobial techniques (Kim and others 2000a; Huang and others 2008). Interestingly, EW has been applied in Japan for several years as an antimicrobial agent. EW exhibits antimicrobial activity against a variety of microorganisms and eliminates most common types of viruses, bacteria, fungi, and spores in a relatively short amount of time (usually within 5 to 20 s) in food products, food processing surfaces, and nonfood surfaces (Ding and others 2015; Hao and others 2015; Hricova and others 2008; Huang and others 2008). Various studies have been conducted on the antimicrobial activity of EW on different products including food handling gloves (Liu and others 2006), cutting boards (Venkitanarayanan and others 1999a; Monnin and others 2012), shrimp (Lin and others 2013; Ratana-Arporn and Jommark 2014; Xie and others

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doi: 10.1111/1541-4337.12200

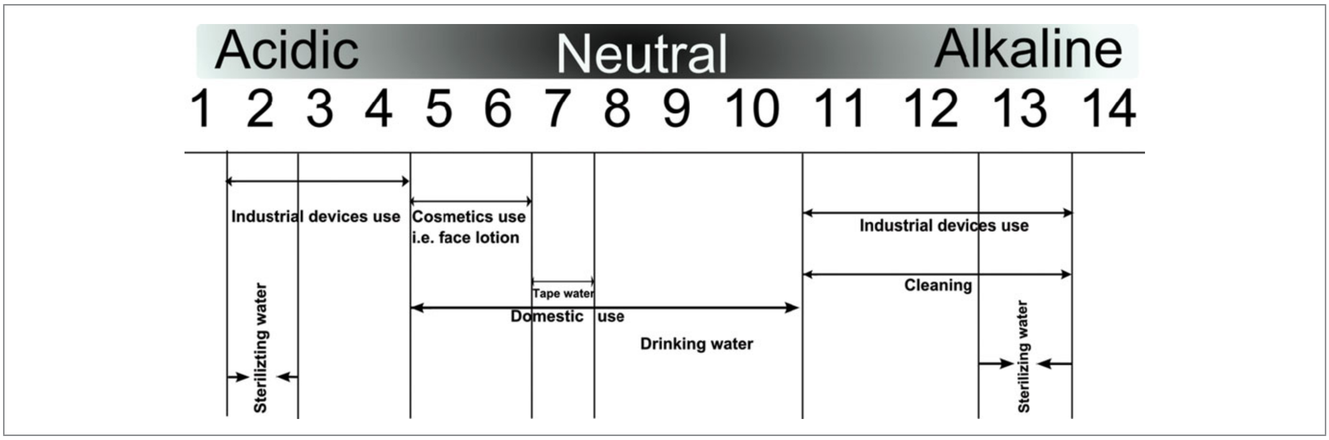

Figure 1–Applications of EW at different pH values in various fields. pH ranges from 0 to 14, with 7 being neutral, less than 7 are acidic while pHs greater than 7 are alkaline. The pH of NEW lies in 7 to 8. AEW has a pH value of ≤3 to 2, whereas AlEW has a pH value of ≥10 to 13. pHs value in between 5.0 to 6.5 and 8.0 to10 are SAEW and SAlEW, respectively.

2012a,b), fish (Phuvasate and Su 2010; Al-Holy and Rasco 2015), beef (Ding and others 2010; Al-Holy and Rasco 2015; Mansur and others 2015b), pork (Rahman and others 2012b, 2013; Wang and others 2012), poultry carcasses (Rahman and others 2012b; Al-Holy and Rasco 2015), fruits (Graca and others 2011; Ding and others 2015; Torlak 2014), and vegetables (Ding and others 2011a; Lee and others 2014; Hao and others 2015; Mansur and Oh 2015c).

However, limitations such as corrosion to equipment and detrimental effects on the quality of treated food products, environment, and human health have been reported for EW (Rahman and others 2010b). Physiochemical characteristics of EW have also been shown to greatly influence its antimicrobial activity (Hsu 2005; Rahman and others 2012a; Forghani and others 2015).

Many characteristics of EW are explained in this review article including the physiochemical properties, generation methodologies, and the impact of these characteristics on the sanitizing efficacy of EW. In addition, applications of EW for microbial control in different areas are discussed.

History

The history of EW in commercial development dates back to more than a century. Although the concept of EW was first developed in Russia, it has been used widely in medical institutions in Japan since 1980 for various purposes including water decontamination, water regeneration, and disinfection (Nikulin 1977; Krivobok and others 1982; Al-Haq and others 2005; Hricova and others 2008). Over time, its use has broadened into various other fields such as livestock management and agriculture (Al-Haq and others 2002; Buck and others 2003; Stevenson and others 2004). Figure 1 illustrates the applications of EW at different pH values in various areas.

Electrolyzed reduced water (ERW) was first introduced in 1931 and applied in agriculture and medical care in 1954 and 1960, respectively. In 1966, ERW was declared to be effective in treating chronic diarrhea, abnormal gastrointestinal fermentation, indigestion, hyperacidity, and as an antacid by the Ministry of Health, Labor, and Welfare, Japan. The Ministry has also authorized the use of ERW as a product for home use (Shirahata and others 2012). With recent technological advances, EW has gained popularity. Owing to these advantages, better equipment for producing EW is now available and EW has become a promising nonthermal disinfectant (Al-Haq and others 2005; Hricova and others 2008).

Production

EW is produced in an electrolysis chamber containing a dilute NaCl solution. The chamber includes a diaphragm (membrane or septum), which is used to separate the cathode and anode (Hricova and others 2008). The complete EW production process is illustrated in Figure 2 and 3. As depicted in Figure 2, current is passed through the EW generator, whereas voltage is generated between the electrodes, with the voltage and current values set at 9–10 V and 8–10 A, respectively (Al-Haqand others 2005). Upon the onset of the electrolysis process, NaCl dissolves in water and dissociates into positively and negatively charged ions (Na^+ and Cl^-, respectively). Meanwhile, hydroxide (OH^-) and hydrogen (H^+) ions are also formed in the solution. The negatively charged ions (OH^- and Cl^-) move toward the anode where electrons are released and hypochlorous acid (HOCl), hypochlorite ion (^-OCl), hydrochloric acid (HCl), oxygen gas (O_2), and chlorine gas (Cl_2) are generated. However, positively charged ions (Na^+ and H^+) move toward the cathode where they gain electrons, resulting in the generation of sodium hydroxide (NaOH) and hydrogen gas (H_2; Al-Haq and others 2005; Hricova and others 2008). Two types of EW are generated simultaneously. At the anode, an acidic solution with a pH of 2 to 3, oxidation reduction potential (ORP) >1100 mV, and available chlorine concentration (ACC) of 10 to 90 ppm is produced. This solution is referred to as acidic electrolyzed water (AEW) or electrolyzed oxidizing water (EOW). Meanwhile, at the cathode, a basic solution with a pH of 10 to 13 and ORP of -800 to -900 mV is produced and this solution is termed as basic electrolyzed water (BEW), AlEW, or ERW. Recently, several researchers have reported the generation of NEW with a pH of 7–8 and ORP of 750–900 mV (Al-Haq and others 2005; Deza and others 2007) and SAEW with pH ranging from 5 to 6.5 and ORP of approximately 850 mV (Nan and others 2010), using single-cell chambers (Figure 3). NEW is produced by mixing the anodic solution with OH^- ions or by using single-cell unit (without diaphragm) from NaCl or HCl (Hricova and others 2008), whereas SAEW is produced by electrolysis of HCl alone or in combination with NaCl in a single-cell unit without diaphragm (Forghani and others 2015). EW can also be stored for future use by conserving in the dark (Len and

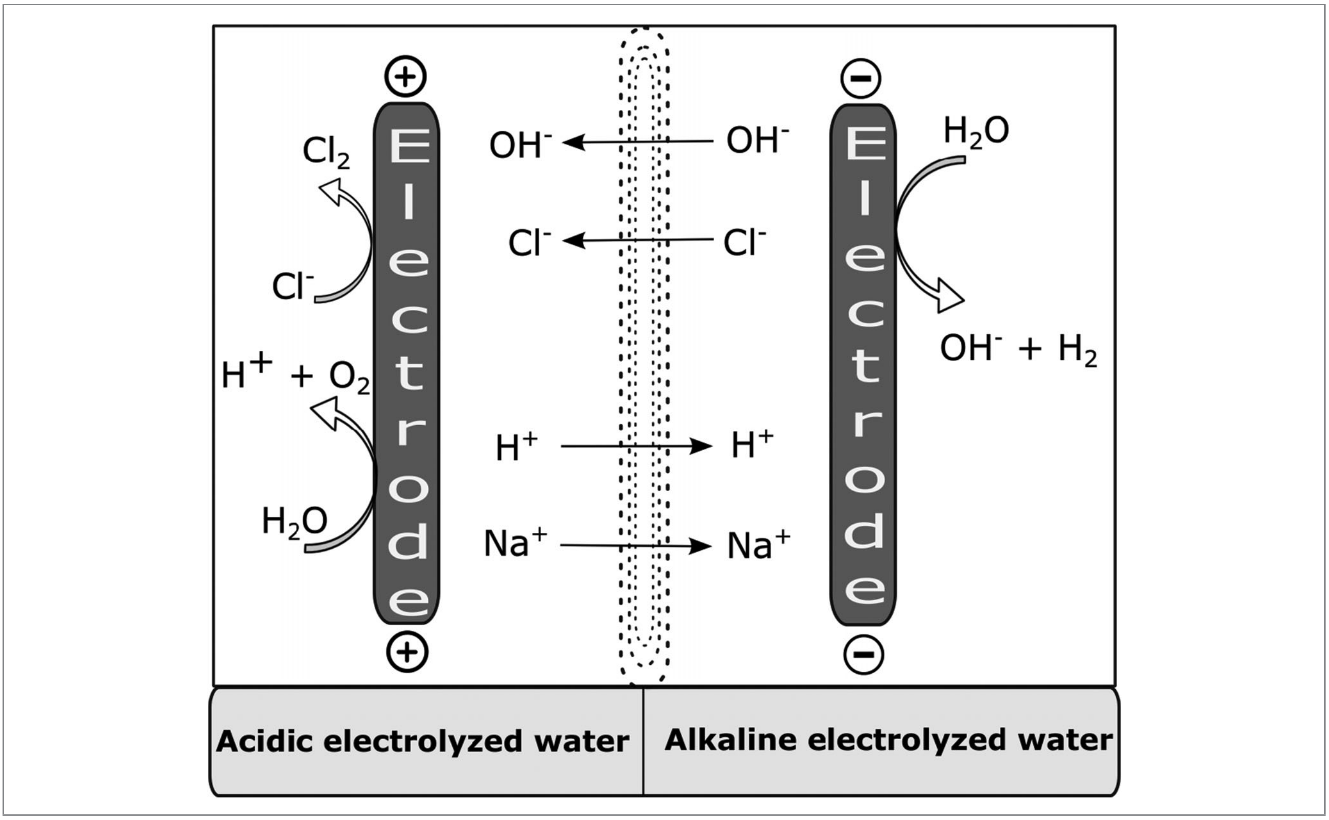

Figure 2–Generation of AEW and AlEW in an electrolytic cell, consisting of anode and cathode connected through an external power supply and separated by a septum or diaphragm. The chemical reactions initiated simultaneously at each electrodes are summarized as follows: at anode: $2\ NaCl \rightarrow Cl_{2\ (g)} + 2\ e^- + 2\ Na^+$, $2\ H_2O_{\ (l)} \rightarrow 4\ H^+_{\ (aq)} + O_{2\ (g)} + 4\ e^-$, $Cl2 + H_2O_{\ (l)} \rightarrow HCl + HOCl$, at cathode: $2\ H_2O_{\ (l)} + 2\ e^- \rightarrow 2\ OH^-_{\ (aq)} + H_{2\ (g)}$, $2\ NaCl + 2OH^- \rightarrow 2NaOH + Cl^-$. AEW is obtained from anode, whereas AlEW obtained from cathode.

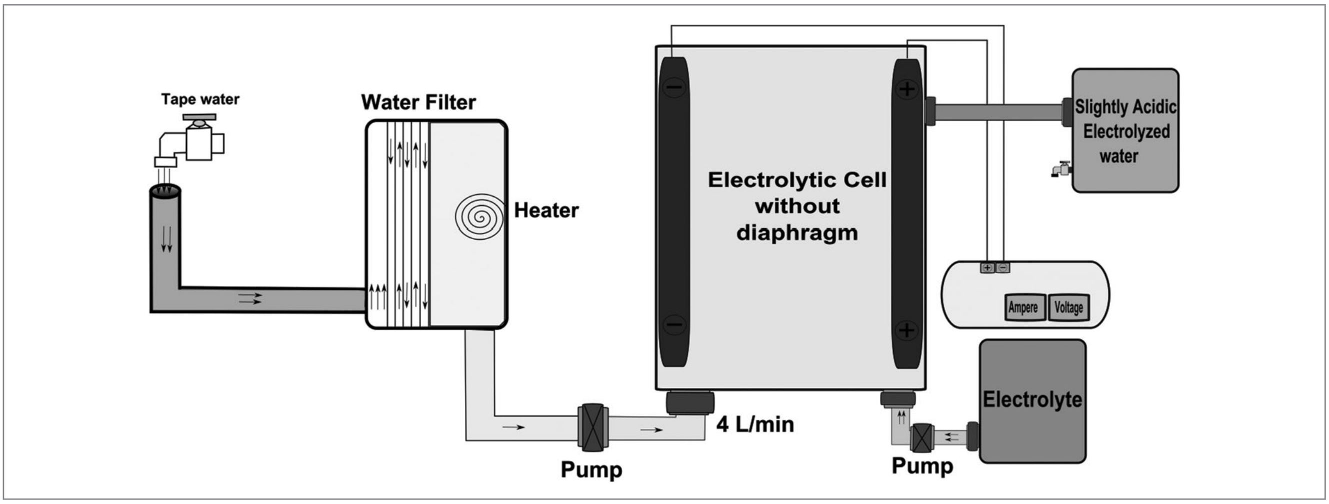

Figure 3–Schematic illustration showing the generation of NEW and SAEW using an electrolytic cell without diaphragm. NEW (pH 7 to 8 and ORP 750 to 900 mV) is produced in the electrolytic cell without diaphragm using electrolytes NaCl or HCl, whereas SAEW (pH 4.5 to 6.5 and ORP approximately 900 mV) is produced from electrolyte HCl alone or in combination with NaCl in the electrolytic cell without diaphragm.

others 2002) or converting it into ice cubes (Koseki and others 2002).

Types of EW-Producing Systems

Many systems for producing EW are available in the world markets such as in the United States, China, Europe, Russia, South Korea, Japan, and Taiwan, among other countries. Japan is the leading manufacturer of EW machines, with over 20 companies manufacturing them. Most of the EW machines can be divided into 2 types: those that contain diaphragms and produce AEW and BEW (machines with 2-cell chambers) and others that do not contain a diaphragm and produce NEW and SAEW (single-cell chambers; Al-Haq and others 2005; Hricova and others 2008). AEW has been reported to exhibit powerful germicidal effects on

Table 1–Various EW producing systems employed in published reports.

Types of EW producing machine	Model and Country	Substrate used	Current used (A)	pH	ORP (mV)	ACC (mg/L)	Reference
AEW	[a]ROX-20TA (Hoshizaki Electric, Japan)	NaCl (0.1appoximately0.2%)	14	2.5	>1000	56	Venkitanarayanan and others (1999b); Kim and others (2000a); Koseki and others (2004); Issa-Zacharia and others (2010a)
NEW	Eurostel® EZ-90 Unit (Ecanet, Palamòs, Girona, Catalonia, Spain)	NaCl (approximately 1%)	305	8.60	72112	280	Abadias and others (2008); Guentzel and others (2008)
SAEW	Apia60 (Hokuty Co., Kanagawa, Japan)	HCl (2%)	3.0	5.8	948	21	Koide and others (2009); Issa-Zacharia and others (2010a); Nan and others (2010)
SAEW	DIPS KI/KII/F, e-suenc Co.,						
Ltd, Seoul, Korea	NaCl (0.1%)	17.1	5.9	79811	35		Quan and others (2010)
SALcEW	D-7,						
Dolki Co. Ltd., Wonju, Korea	NaCl (0.9%)	1.15 to 1.17	6.2 to 6.3	5000	5		Rahman and others (2010a, 2012b)

ACC, available chlorine concentration (Cl_2, $^-$OCl, and HOCl); AEW, acidic electrolyzed water; NEW, neutral electrolyzed water; ORP, oxidation reduction potential; SAEW, slightly acidic electrolyzed water; SALcEW, slightly acidic low concentration electrolyzed water. [a]ROX-20TA also produces alkaline electrolyzed water.

pathogenic bacteria, which need to be eliminated for ensuring food safety (Hricova and others 2008). However, BEW, with its strong reducing potential, can be used to remove dirt and grease from items such as chopping boards, kitchen utensils, and others (Hsu 2005; Hricova and others 2008). Commercial AEW generators are of 3 main types based on the automatic control systems they are equipped with. The first type allows users to fix the brine flow rate, whereas the machines automatically adjust voltage and amperage. The second type allows users to choose the amperage and voltage, whereas the machines regulate the brine flow rate accordingly. The third type allows the users to set a chlorine concentration level. Based on this setting, the machines alter the amperage and/or voltage and brine flow rate automatically (Hsu 2003; Hricova and others 2008). The various EW-producing systems that have been employed so far in published reports are summarized in Table 1. The most common machine among these is ROX TA-20 (HOSHIZAKI Electric, Japan; Al-Haq and others 2005). The physiochemical properties of EW vary depending on the concentration of sodium chloride, current values, and time of electrolysis or flow of water (Kiura and others 2002; Hricova and others 2008). Recently, Forghani and others (2015) developed a dynamic SAEW production system that provides a basis for the development of SAEW generators for household use as well as for commercial use in the food industry.

Basic Properties of EW

EW is a relatively novel antimicrobial agent that is highly effective against foodborne pathogens attached to cutting boards (Venkitanarayanan and others 1999a), surfaces of poultry (Park and others 2002a), organisms that cause spoilage of vegetables (Izumi 1999), cell suspensions (Venkitanarayanan and others 1999b), and so on. As stated previously, NaCl is the singular chemical that is used in the EW production process. During electrolysis, a high amount of ACC along with lower amounts of H_2O_2 and O_3 are produced. Overall, the process has significantly lower adverse effects on nature and the environment (Kim and others 2000b). However, the antimicrobial activity of EW and its mechanism of action are still not completely understood. Some scientists consider the presence of chlorine in EW as the major factor responsible for its antimicrobial activity, whereas others consider ORP as the major governing factor (Al-Haq and others 2005). Various factors such as current, water flow rate, electrolyte, salt concentration, electrode materials, storage conditions, water hardness, and water temperature have been reported to affect the physicochemical properties of EW and have been thought to be responsible for the sanitization effect of EW.

Influence of ACC, pH, and ORP on the antimicrobial properties of EW

The antimicrobial efficacy of EW is highly influenced by ORP, concentration of chlorine (Cl_2, $^-$OCl, and HOCl), and pH (Len and others 2000). The pH of EW plays an important role in the formation of various chlorine species. Chlorine is strongest in the HOCl form and exhibits 80 times greater sanitizing power than $^-$OCl when the pH of the solution is 5.0 to 6.5 (Cao and others 2009). However, HOCl dissociates to hypochlorite ions ($^-$OCl) at high pH and chlorine gas (Cl_2) at low pH values (Figure 4). HOCl infiltrates the membranes of germ cells and produces hydroxyl radicals, which exert antimicrobial action via oxidation occurring in the key metabolic frameworks (Huang and others 2008). The ORP and ACC of EW were found to decline substantially with an increase in pH from the acidic (pH 2.5) to the basic (pH 9.0) region. When the pH reached a value of 9.0, the ability to inactivate all organisms was found to be diminished (Rahman and others 2010a). AEW has a low pH and this is known to be responsible for the decrease in the production of bacteria and for making the bacterial cells more vulnerable towards dynamic chlorine by making their external layer more susceptible to HOCl (Park and others 2004). Park and others (2004) examined the influence of chlorine and pH of AEW in inactivating *Listeria monocytogenes* (*L. monocytogenes*) as well as *Escherichiacoli* O157:H7 (*E. coli* O157:H7). AEW was shown to be extremely effective in inactivating these organisms in a wide range of pH (2.6 to 7.0), if adequate amounts of free chlorine (>2 mg/L) are available. A few researchers have proposed that high ORP is the main factor determining the antimicrobial action of AEW (Kim and others 2000b; Liao and others 2007; Huang and others 2008). Owing to the high ORP of AEW, oxidation may occur, harming various

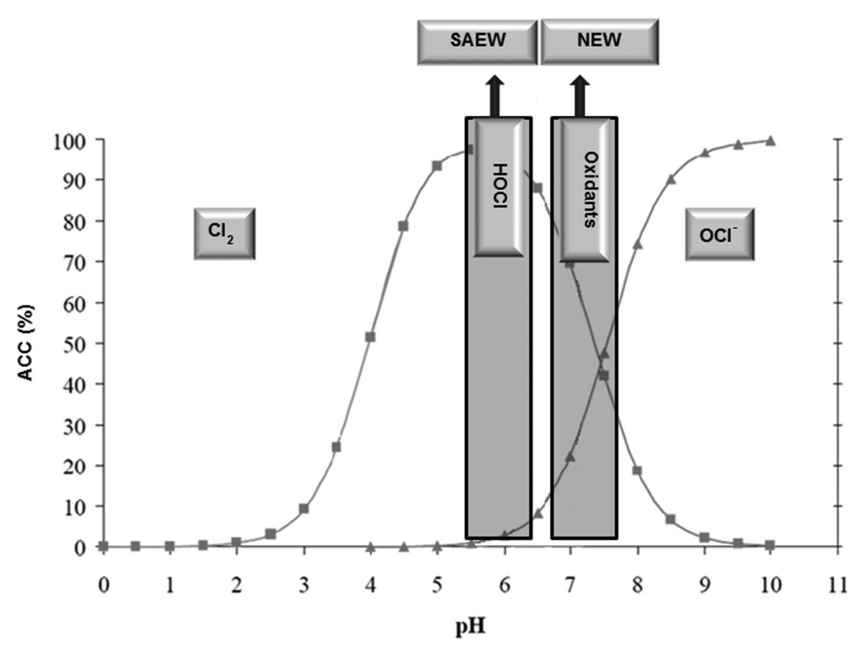

Figure 4–Changes in ACC (%) in EW at various pH values. ACC consist of HOCl, OCl^- and Cl_2 gas. At reduced pH (0 to 2.0) chlorine is present in gas form. Cl_2 concentration decreased with increasing pH, and at pH 5.0 to 6.5, a high amount of HOCl was formed. HOCl dissociated into OCl^- at pH 6.5 to 7.5. EW at pH 5.0 to 6.5 and pH 7.0 to 8.0 is known as SAEW and NEW, respectively.

layers of cells, causing the oxidation of sulfhydryl mixtures on cell surfaces, and disturbing metabolic pathways inside the cell. This would prompt the inactivation of bacterial cells (Liao and others 2007). In principle, the low pH and high ORP of AEW act synergistically with HOCl in inactivating microorganisms (Park and others 2002b, 2004; Bari and others 2003; Liao and others 2007). Besides, Stevenson and others (2004) found complete loss of bactericidal activity when the ORP decreased to less than 848 mV. However, Rahman and others (2012a) observed ≥ 5.0 log CFU/mL reduction in pathogenic bacteria in the case of treatment with EW having an ORP of 500 to 700 mV. However, Koseki and others (2001a) noted that ORP is not the primary factor affecting the disinfection process, because ozonated water with higher ORP did not exhibit greater antimicrobial effect compared to AEW with lower ORP. Moreover, they reported that the free chlorine in AEW (mainly in the form of HOCl) produces OH^-, which has strong germicidal effect.

Relationship between current, water flow rate, and salt concentration in EW

Flow rate of electrolytes, water, and current indirectly influence the sanitizing efficacy of EW. For instance, an increase in the water flow rate causes an increase in the electric current due to the electrolysis of a greater amount of salt solution per unit time (Hsu 2003). Contrary to these findings, Hsu (2005) found a negative correlation between the water flow rate, ACC, and ORP. In his study, increasing the water flow rate decreased the total chlorine concentration and ORP of the EW. This might be explained by considering that the machine control action of the EW generator could have affected the ORP level of EW. The amperage of the water generator influences the concentration of chlorine, which ultimately increases or decreases the effectiveness of EW (Park and others 2001). Rahman and others (2012a) showed the impact of current flow on the sanitizing efficacy of EW against foodborne pathogens. They found that when the current was increased from 1.15 to 1.45 A, a log reduction of 4.9–5.6 CFU/mL for both *E. coli* O157:H7 and *L. monocytogenes* was achieved. In addition, the values of ORP, ACC, and pH increased with increase in the current value. Hsu (2005) has also reported similar results and has demonstrated that high salt concentration in the feeding solution resulted in high salt concentration and high conductivity of EW. Salinity was linearly correlated to conductivity. Moreover, there are a linear correlation between the amount of NaCl added and the amount of HOCl produced during the electrolysis process (Al-Haq and others 2002, 2005). Kiura and others (2002) also found positive correlations between the free chlorine concentration, NaCl concentration, and electrolysis time. This finding is supported by the fact that when the flow rate of water and salt concentration increased, the separation efficacy of the ion exchange membrane and electrolysis efficacy of the electrolysis cell were significantly decreased.

Influence of storage conditions on the properties of EW

The sanitizing applications of EW have been limited, owing to the evaporation of Cl_2 over time and the ensuing HOCl breakdown, particularly in open conditions (Len and others 2002; Al-Haq and others 2005; Hricova and others 2008). When stored under closed conditions, EW loses chlorine by self-decomposition. The loss of chlorine by self-decomposition under closed conditions is, however, lower than the chlorine loss by evaporation under open situations (White and others 1998). The physiochemical properties of EW exhibit dramatic changes over time under both closed and open conditions (Len and others 2002; Rahman and others 2012a). Under open and closed storage environments, the ACC of low-concentration electrolyzed water (LcEW) fell from 10 to 0 mg/L over 7 and 21 d, respectively. However, the pH of LcEW stored under both open and closed conditions increased through 28 d of storage, even as the ORP values decreased. It has also been shown in this study that the bactericidal activity of LcEW against cell suspensions of *E. coli* O157:H7 and *L. monocytogenes* was sustained up to 6 d under open and 14 d under closed storage conditions (Rahman and others 2012a). Len and others (2002) showed that the chlorine in AEW stored under open conditions was entirely lost after 30 h of agitation and 100 h under quiescent conditions. However, chlorine loss is not affected by lighting during storage. Further, the free chlorine in AEW dropped by 80% over 2 h of stirring, whereas the ORP value remained constant, indicating the existence of other strong oxidants (Bonde and others 1999). The impact of temperature on the storage conditions of EW was previously studied. It was shown that AEW stored at 4 °C was more stable than that stored at 25 °C (Fabrizio and Cutter 2003). Nagamatsu and others (2002) also observed similar results. However, different types of EW act differently when stored under the same conditions. AEW has been shown to be less stable than NEW throughout the storage period (Nagamatsu and others 2002; Cui and others 2009). Hsu and Kao (2004) reported that the properties of AEW such as ORP, electric conductivity, and pH did not change remarkably, whereas dissolved oxygen (DO) content and ACC decreased significantly during storage.

Influence of electrolyte and electrode materials on the properties of EW

The type of electrolyte, electrolyte flow rate, and choice of electrode materials also influence the properties and sanitization potential of EW. Various types of electrolytes including NaCl, $MgCl_2$, KCl, and HCl have been utilized in EW production (Al-Haq and others 2005; Hricova and others 2008; Pangloli and others 2013). It has also been stated that the ACC value is positively influenced by the concentration of electrolyte, rather than the type of EW. Forghani and others (2015) suggested high sanitizing activity of EW at increased electrolyte concentrations. This can be explained by the fact that high concentrations of electrolyte may result in high conductivity, which could possibly increase chlorine production. Meanwhile, an increase in pH occurs due to an increase in the concentration of NaCl, which boosts the production of SAEW with pH in a satisfactory range. Electrochemical disinfection studies traditionally employ platinum as the anode material (Quan and others 2010; Rahman and others 2012a; Forghani and others 2015). Jeong and others (2009) found that the choice of electrode materials plays a key role in the production of oxidants. Moreover, the order of electrode materials arranged in terms of the production of active chlorine was found to be as follows: $Ti/IrO_2 > Ti/RuO_2 > Ti/Pt–IrO_2 >$ BDD > Pt. Besides HOCl, OCl, and Cl_2, they also observed that the generation of reactive oxygen species including OH^-, O_3, and H_2O_2 was influenced by the type of material used as the anode. In addition, various reaction parameters, including applied current or voltage, temperature, pH, electrolyte composition, electrode material, and type of electrolysis, may influence the production of such strong oxidants. Among these, the most important parameter is the electrode material, which governs the production of oxidants and other species (Martinez-Huitle and Brillas 2008).

Influence of water temperature and hardness on the properties of EW

Many studies have shown the influence of water temperature and hardness on the antimicrobial efficacy of EW (Fabrizio and Cutter 2003; Cao and others 2009; Forghani and others 2015; Rahman and others 2010b). Evidently, the sanitizing efficacy of SAEW is improved with increasing temperature (Cao and others 2009; Ding and others 2011a; Koide and others 2011). Fabrizio and Cutter (2003) tested the effectiveness of AEW against *L. monocytogenes* and *Salmonella typhimurium* at 4 and 25 °C and found that the maximum reduction (>8 log CFU/mL) occurred at 25 °C. Similar results have also been observed in investigations by Rahman and others (2010b), who reported that treating various bacterial species such as *S. typhimurium*, *L. monocytogenes*, *Staphylococcus aureus*, and *E. coli* O157:H7 for about 1 min at about 50 °C leads to their complete elimination (reduction of approximately 7.42 to 8.02 log CFU/mL). The logarithmic rate of reduction was found to increase significantly with an increase in the dipping temperature from 4 to 50 °C. Contrary to this, Forghani and others (2015) showed that SAEW obtained from preheated water (40 °C) exhibited substantially higher rates of reduction of *L. monocytogenes* and *E. coli* O157:H7, compared to heated SAEW (40 °C). The phenomenon has been attributed to the partial loss of ACC that occurs upon heating SAEW at 40 °C.

Water hardness is a relatively new concept in EW-related studies and so far, only 2 studies (Pangloli and Hung 2013; Forghani and others 2015) have examined the influence of water hardness on the sanitizing efficacy and properties of SAEW. Water hardness has shown a positive impact on the properties (free chlorine, pH, and ORP) of EW and consequently, on the antimicrobial effect (Pangloli and Hung 2013). It was demonstrated that an increase in the hardness of water causes subsequent increases in the values of ORP and free chlorine, causing a decrease in the pH value of EW, resulted in decrease in bactericidal activity. They concluded that pH had no significant effect on the overall antimicrobial activity of EW. Forghani and others (2015) further evaluated the impact of water hardness and heating on the properties of SAEW. Their results showed that the pH of SAEW increases when the hardness of water is increased using 5% HCl and 2 M NaCl at a flow rate of 1.5 mL/min. Furthermore, the results showed that preheating of water is a better approach compared to the post-production heating of SAEW, and results in higher ACC values and therefore, better sanitization efficacy. These results demonstrate that water hardness is a crucial factor that must be considered in the optimization and production of SAEW. It can be concluded that the sanitizing efficacy of EW depends on various parameters from production to applications. Each of these factors have exhibited some influence on the sanitizing potential of EW. A standard operating procedure (SOP) for manipulating EW needs to be developed and implemented in order to ensure long-lasting sanitizing effect of EW.

Advantages and Disadvantages

EW has shown numerous advantages over its toxic counterparts in various areas including food, agriculture, and the medical industry. As stated previously, EW is produced in an environmentally friendly fashion from table salt (NaCl) and distilled water (Hricova and others 2008). Interestingly, EW returns to its normal form after use and poses no threat to humans and the environment (Al-Haq and others 2005). The main advantage of using EW is the ability for on-site production, thus circumventing problems associated with chlorination including the transport, storage, and handling of dangerous chlorine (Jeong and others 2007). EW is active against a broad spectrum of bacteria and possesses nonselective antimicrobial properties. Therefore, it is hypothesized that EW does not promote the growth of bacterial resistance (Hricova and others 2008). In addition, the sensory quality of food products is not negatively affected by the use of SAEW, NEW, and slightly alkaline EW (SAlEW; Hricova and others 2008; Rahman and others 2010c, 2011, 2012b, 2013). Moreover, EW is cost-effective and costs only ca. 0.04 $/L as opposed to its counterpart

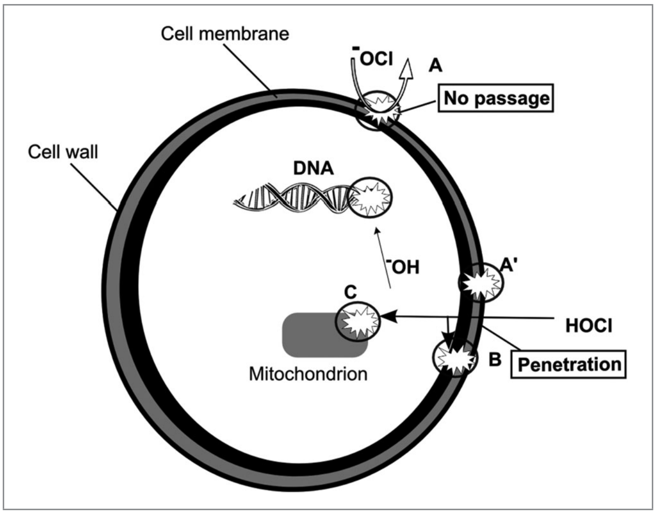

Figure 5–Model representing the germicidal activity of EW. Ionized $^{-}$OCl cannot cross the microbial membrane and has shown poor germicidal activity. $^{-}$OCl only attack on the outer membrane of the cell (circle A). HOCl is the active species in the germicidal action. HOCl has neutral charge and can diffuse through the cell membrane. HOCl can attack on the outer membrane (circle A') and also inside the cell (circle B and C).

glutaraldehyde, which costs ca. 9.98 \$/L. The electricity charges, cost of chemical salts, and water are the major operating expenses involved in running the EW production machine, besides the initial investment in purchasing the EW generator (Hricova and others 2008).

However, there are some disadvantages associated with EW, which limit their widespread application. The disadvantages that need to be considered include: (i) the relatively high initial cost of equipment (Hricova and others 2008); (ii) the tendency for EW to lose its antimicrobial potential quickly, if it is not continuously supplied with Cl_2, H^+, and HOCl by electrolysis (Kiura and others 2002); (iii) reduction in the concentration of chlorine over time, which reduces the bactericidal activity of EW (Al-Haq and others 2005); (iv) discomfort to the operator caused by the pungent chlorine gas generated by some EW generators when operated at $pH < 5$; (v) phytotoxicity, irritation of hands, and corrosion caused by the free chlorine content or high ORP during the use of AEW (Al-Haq and others 2005; Hricova and others 2008); (vi) reduction in antimicrobial activity by inappropriate storage and the presence of organic matter in EW (Oomori and others 2000; Koseki and others 2001a; Hricova and others 2008); and (vii) finally, the lack of data on ACC after electrolysis, although chlorine is now considered to be the active agent in EW.

Mechanism of Germicidal Action

Knowledge of the mode of action of EW will enable better dosing for various applications in the food chain and other areas. However, reports on the mechanism of the germicidal action of EW are scarce. It is well known that the active chlorine species (Cl_2, HOCl, and $^{-}$OCl) contribute to the inactivation of microbial cells. Besides active chlorine, other oxidants such as the reactive oxygen species (ozone and hydrogen peroxide) are generated during electrolysis, which also contribute to the antimicrobial efficacy of EW (Jeong and others 2007, 2009). Fukuzaki (2006) developed a model (Figure 5) to explain the germicidal action of sodium hypochlorite. The germicidal action of HOCl was attributed to its penetration into microbial cells across the cell walls and membranes. This model elucidates that the germicidal activity of EW is governed by the abilities of HOCl and $^{-}$OCl to diffuse through the microbial cell membrane. Ionized $^{-}$OCl is unable to penetrate the microbial cell membrane because of the existence of the lipid bilayer, which is the hydrophobic layer of the plasma membrane. Occasionally, some structures of the microbial cell wall also protect the cell from $^{-}$OCl penetration. Therefore, $^{-}$OCl imparts oxidizing action only from outside the cell (circle A). In the first step of disinfection by $^{-}$OCl, the rupture or disintegration of the microbial cell wall and membrane appear to occur, following which $^{-}$OCl would inactivate the functional proteins localized in the plasma membrane. This is responsible for the poor germicidal activity of $^{-}$OCl. On the other hand, HOCl can penetrate the lipid bilayer of the plasma membrane by passive diffusion. The penetration of HOCl is due to its electrical neutrality and its modest molecular size, which is comparable to that of water. This is also true of other neutral and small molecules such as H_2O_2. As a result, HOCl can attack the microbial cell not only from the outside (circle A' in Figure 5), but also from within the cell (circles B and C), thereby accelerating the inactivation rate and enhancing the germicidal activity. The germicidal activity of HOCl or $^{-}$OCl is believed to be due to the inhibition of enzyme activity essential for microbial growth, damage to the membrane and DNA, and perhaps deterioration in membrane transport capacity, although these factors have not been fully examined.

Applications of EW

EW application in suspensions

The antimicrobial potential of EW against various microorganisms is depicted in Table 2. EW showed strong antimicrobial activity in vitro, with an average reduction of >6 log CFU/mL reported for a variety of bacteria (Hricova and others 2008). Comparisons between the results obtained from the application of EW in suspensions are relatively difficult, owing to the different conditions adopted. In addition, foodborne pathogens show different sensitivities towards EW. An obvious difference in sensitivity to AEW was observed between *Proteus mirabilis (P. mirabilis)*, *S. aureus*, *Mycobacterium avium* subsp. *avium*, *Enterococcus faecium*, and *Pseudomonasaeruginosa*. *P. mirabilis* and *S. aureus* were more sensitive than *M. avium* subsp. *avium*, *E. faecium,* and *P. aeruginosa* toward AEW (Fenner and others 2006). Rahman and others (2010a) evaluated the effect of ACC and exposure time of SAEW on the elimination of foodborne pathogens in vitro and reported that with increase in the exposure time, reduction in the value of log CFU/mL decreased. Interestingly, 1 min of exposure significantly ($P < 0.05$) reduced the log CFU/mL value, whereas the reductions were not significant for 3, 5, and 10 min of exposure time. In addition, in this study, the low concentration of available chlorine (5 ppm) significantly ($P < 0.05$) reduced the log CFU/mL value compared to a relatively high concentration of chlorine (50 ppm), regardless of exposure time. In contrast, complete inactivation of *E. coli* O157:H7 and *L. monocytogenes* were observed by treating with AEW containing 56 ppm ACC for 30 s at 24 °C (Kim and others 2000a). Quan and others (2010) studied the effect of SAEW containing different concentrations of chlorine against *Vibrio vulnificus*. The results of the study showed that no viable cells were detected when the ACC was >20 ppm and treatment time was more than 15 s. They concluded that the bactericidal activity of SAEW only depends upon ACC and not on the exposure time. Ovissipour and others (2015) found a 6.88 log CFU/mL reduction in *E. coli* O104:H4 by treating with strong acidic electrolyzed water (StAEW) for 180 s. However, *E. coli* O104:H4 was

Table 2–Applications of EW against various microorganisms in suspension.

Microorganisms	EW type	Exposure time (min)	Reduction (log CFU/mL)	[a]Chlorine conc. (ppm)	pH	ORP (mV)	Temp.	Reference
Escherichia coli	StAEW	1	6.0	50.3	2.6	1140	20	Issa-Zacharia and others (2010b)
	SAEW	1	5.0	23.7	5.6	940	20	Issa-Zacharia and others (2010b)
	SAEW	2	6.2	23.7	5.6	940	20	Issa-Zacharia and others (2010b)
	NEW	1	>5.4	89	8.55	733	20	Abadias and others (2008)
E. coli O157:H7	StAEW	1	6.0	50	2.6	1100	35	Rahman and others (2010a)
	LcEW	1	6.0	5	6.3	500	35	Rahman and others (2010a)
	LcEW	1.5	6.4	10	6.8	700	23	Rahman and others (2012a)
	SAEW	3	5.2	1.5	6.5	805	25	Nan and others (2010)
	NEW	1	ND	21	6.3	265	20	Cui and others (2009)
	AEW	1	ND	25	3.0	1079	20	Cui and others (2009)
	AEW	1	6.3	63	2.4	1183	22	Pangloli and Hung (2013)
E. coli O104:H4	StAEW	2	5.1	20	3.1	1150	20	Ovissipour and others (2015)
	SAEW	2	4.2	10	3.5	950	20	Ovissipour and others (2015)
	StAlEW	2	1.5	NA	11.1	-840	20	Ovissipour and others (2015)
	SAlEW	2	1.5	NA	10.4	-715	20	Ovissipour and others (2015)
Salmonella spp.	NEW	1	>5.5	89	8.5	733	20	Abadias and others (2008)
	StAEW	1	6.1	50.6	2.6	1140	20	Issa-Zacharia and others (2010b)
	SAEW	2	6.1	23.7	5.6	940	20	Issa-Zacharia and others (2010b)
	StAEW	1	6.1	50	2.6	1100	35	Rahman and others (2010a)
	LcEW	1	6.3	5	6.3	500	35	Rahman and others (2010a)
S. enteritidis	AEW	2	ND	6	2.6	1096	20	Cao and others (2009)
	SAEW	2	ND	6	6.4	265	20	Cao and others (2009)
	NEW	1	ND	21	6.3	265	20	Cui and others (2009)
	AEW	1	ND	25	3.0	1079	20	Cui and others (2009)
Staphylococcus aureus	StAEW	1	5.9	50.3	2.6	1139	20	Issa-Zacharia and others (2010b)
	SAEW	2	5.9	23.7	5.6	940	20	Issa-Zacharia and others (2010b)
	StAEW	1.5	6.7	45.3	2.6	1140	20	Issa-Zacharia and others (2010a)
	SAEW	1.5	5.3	21.2	5.8	948	20	Issa-Zacharia and others (2010a)
	StAEW	1	6.6	50	2.6	1100	35	Rahman and others (2010a)
	LcEW	1	6.7	5	6.3	500	35	Rahman and others (2010a)
	LcEW	5	7.1	5	6.2	520	35	Wang and others (2011)
	SAEW	3	2.0	6	6.4	842	25	Nan and others (2010)
Listeria monocytogenes	StAEW	1	6.0	50	2.6	1100	35	Rahman and others (2010a)
	LcEW	1	6.2	5	6.3	500	35	Rahman and others (2010a)
	LcEW	1.5	6.7	10	6.8	700	23	Rahman and others (2012a)
	AEW	1	7.4	63	2.4	1183	22	Pangloli and Hung (2013)
	StAEW	2	ND	20	3.1	1150	20	Ovissipour and others (2015)
	SAEW	2	ND	10	3.5	950	20	Ovissipour and others (2015)
	StAlEW	2	1.9	NA	11.1	−840	20	Ovissipour and others (2015)
	SAlEW	2	1.9	NA	10.4	−715	20	Ovissipour and others (2015)
Campylobacter jejuni	StAEW	2	ND	20	3.1	1150	20	Ovissipour and others (2015)
	SAEW	2	ND	10	3.5	950	20	Ovissipour and others (2015)
	StAlEW	2	2.6	NA	11.1	−840	20	Ovissipour and others (2015)
	SAlEW	2	2.5	NA	10.4	−715	20	Ovissipour and others (2015)
L. innocua	NEW	1	>5.5	89	8.5	733	20	Abadias and others (2008)
Erwinia carotovora	NEW	1	>5.7	89	8.5	733	20	Abadias and others (2008)
Alicyclobacillus acidoterrestris spores	NEW	5	4.2	48	7.5	770	20	Torlak (2014)
Vibrio vulnificus	SAEW	1	ND	35	5.9	798	RT	Quan and others (2010)
V. parahaemolyticus	SAEW	1	ND	35	5.9	798	RT	Quan and others (2010)
	StAEW	2	ND	20	3.1	1150	20	Ovissipour and others (2015)
	SAEW	2	ND	10	3.5	950	20	Ovissipour and others (2015)
	StAlEW	2	3.1	NA	11.1	−840	20	Ovissipour and others (2015)
	SAlEW	2	2.6	NA	10.4	−715	20	Ovissipour and others (2015)
Aeromonas hydrophila	StAEW	2	ND	20	3.1	1150	20	Ovissipour and others (2015)
	SAEW	2	ND	10	3.5	950	20	Ovissipour and others (2015)
	StAlEW	2	2.8	NA	11.1	−840	20	Ovissipour and others (2015)
	SAlEW	2	2.4	NA	10.4	−715	20	Ovissipour and others (2015)
Fungi								
Monilinia fructicola	NEW	10	ND	25	6.5–6.7	800–900	25	Guentzel and others (2010)
Botrytis cinerea	NEW	10	ND	25	6.5–6.7	800–900	25	Guentzel and others (2010)

AEW, acidic electrolyzed water; LcEW, low concentration electrolyzed water; NA, not available; ND, not detected on direct plate; NEW, neutral electrolyzed water; ORP, oxidation reduction potential; RT, room temperature; SAEW, slightly acidic electrolyzed water; SAlEW, slightly alkaline electrolyzed water; StAEW, strong acidic electrolyzed water; StAlEW, strong alkaline electrolyzed water.

[a] Chlorine concentration represents available chlorine concentration (Cl_2, ^{-}OCl, and HOCl).

significantly more resistant to AlEW compared to AEW. Their results demonstrated that the bactericidal activity of StAEW (ACC 20 ppm) was more effective than SAEW (ACC 10 ppm), from the point of view of inactivating *E. coli* O104:H4. AlEW were found to reduce cell numbers by 1 to 3 log ($P < 0.05$). Interestingly, under the same treatment conditions, no viable cells were detected for *Vibrio parahaemolyticus, Campylobacter jejuni*, *L. monocytogenes*, and *Aeromonas hydrophila* within 2 min at 20 °C.

The optimal pH for bacterial growth is 4–9. The physiochemical properties of EW also change with change in the pH value. At a chlorine concentration at 300 ppm, the ORP values changed from 1150 to 750 upon changing the pH from 4 to 9 (Yang and others 2003). The optimal ORP range for aerobic bacterial growth is +200 to 800 mV, whereas the optimal range for anaerobic bacterial growth is −700 to +200 mV. The effects of pH on the efficacy of AEW in inactivating *E. coli* O157:H7 has been reported. The logarithmic reduction in *E. coli* O157:H7 increased from 5.68 to 6.06 with decrease in pH from 8 to 5 (Pangloli and Hung 2013). Rahman and others (2012a) successfully reduced *E. coli* O157:H7 by 5.9 log CFU/mL at pH 6.8 and ACC of 10 ppm. However, bacterial spores are less sensitive to EW than vegetative cells (Table 2). Torlak (2014) reported a reduction in the spores of *Alicyclobacillus acidoterrestris* by 4.25 log CFU/mL by treatment with NEW containing 50 ppm of active chlorine at pH 7.52 for 5 min. In this study, the efficacy of NEW against spores decreased with decrease in the exposure time. Log CFU/mL values of 2.58 and 0.54 were reported for 3 and 1 min, respectively. In another study, *Bacillus cereus* spores reduced by 3.5 orders of magnitude when exposed to AEW for 2 min, whereas the vegetative cells were reduced by 8.0 log CFU/mL within 0.5 min (Kim and others 2000a). Interestingly, when AEW with 43 ppm of ACC was utilized for 5 min, over 6 orders of magnitude reduction in both the spores and vegetative cells were recorded. In addition, increase in exposure time resulted in enhanced reduction in spores. When AEW containing 20 to 30 ppm of active chlorine was applied for 15 min, *Aspergillus parasiticus* spores having an initial count of 1000 was inactivated (Suzuki and others 2002; Vorobjeva and others 2004). Hence, the factors (ORP, pH, ACC, temperature, and treatment time) that influence the antimicrobial activity of EW may be monitored before EW treatment is applied to targeted microorganisms.

EW application in vegetables and fruits

The sanitizing potential of various types of EW toward vegetables is depicted in Table 3. LcEW treatment of lettuce for 60 s reduced the *E. coli* O157:H7 and *L. monocytogenes* counts by 2.49 and 3.76 log CFU/g, respectively (Rahman and others 2010a). Guentzel and others (2008) reported the effectiveness of AEW treatment on spinach and lettuce (ACC 100–120 ppm, pH 6.3, exposure time 10 min) against *S. typhimurium*, *E. coli, L. monocytogenes, S. aureus,* and *Enterococcus faecalis*. A total reduction of 4.0 to 5.0 and 2.43 to 3.81 log CFU/mL was achieved for all types of bacteria in spinach and lettuce, respectively, except for *E. coli* in lettuce, which was reduced by 0.24 to 0.25 log CFU/mL. The disinfection efficacy of SAEW treatment on oyster mushroom (Ding and others 2011a) and fresh-cut cabbage (Koide and others 2009) was also studied and approximately 1.35 to 1.50 log reductions in total bacteria were obtained. Koide and others (2009) also reported reductions of 1.5 log and 1.3 log CFU/g for total aerobic bacteria and 1.3 log reductions for yeasts and molds, when fresh-cut cabbage was dipped in SAEW for 10 min. Furthermore, AEW was also as effective as chlorine in reducing *L. monocytogenes*, *E. coli* O157:H7, and *Salmonella* populations on leafy greens (Stopforth and others 2008). Yarahmadi and others (2012) reported that AEW may be used as a suitable alternative to chlorine for the treatment of leafy greens. The exposure time plays a key role in reducing the microbial count in fresh vegetables. Some authors have reported that increasing the exposure time above 1 or 2 min has no effect on the bactericidal activity in lettuce (Adams and others 1989; Beuchat and others 1998). Abadias and others (2008) also reported that increasing the exposure time from 1 to 5 min in the cases of treatment with NEW or sodium hypochlorite did not significantly affect the antimicrobial activity on different fresh-cut vegetables. These studies showed that the activity of EW was compromised over a relatively short length of time, which could be attributed to the dissociation of HOCl or interference from some other factor such as organic matter. Rahman and others (2011) reported the sanitizing effect of AEW against *E. coli* O157:H7 and *L. monocytogenes* present on shredded carrots. Significant reductions in the total bacteria, yeast, and fungi on the carrots were observed. An increase in the log CFU/g reduction of total bacteria, yeast, and fungi from 0.22 to 2.67 was observed when the dipping temperature was increased from 1 to 50 °C. Recently, Mansur and others (2015a) also studied the impact of temperature on the sanitizing efficacy of SAEW (ACC 5 ppm, pH 6.28, exposure time 3 min) on fresh-cut kale. The treatment resulted in >1.5 and 2 log CFU/g reduction in *L. monocytogenes* at 4 and 7 °C, respectively.

EW has also shown great potential for microbial reduction in fruits and the results are depicted in Table 3. Both AEW and NEW effectively reduced the total number of *Listeria innocua*, *S. choleraesuis,* and *E. coli* by 0.9 to 2.15 log CFU/g in processed apple (Graca and others 2011). In another study, Deza and others (2003) reported the effectiveness of NEW treatment on tomatoes against *E. coli*, *S. typhimurium*, *L. monocytogenes,* and *Salmonella enteritidis*. Greater than 5 log CFU/cm^2 reduction was observed. In the case of strawberries, 0.96 and 0.93 log reductions were achieved for yeasts and molds and total aerobic bacteria, respectively, upon treating with SAEW containing 34 ppm active chlorine at pH 6.49 (Ding and others 2015). These results also agree with those reported by Hao and others (2011), where the treatment of fresh-cut cilantro in SAEW for 5 min resulted in 1.56 and 1.64 log CFU/g reductions in total aerobic bacteria and yeasts and molds, respectively. In summary, SAEW is a promising nonthermal food sanitizer that may be considered as an alternative to NaOCl solution and would lessen the amount of active chlorine used in fresh produce.

EW applications in poultry and meat

Microbial contamination in pork and meat is a vital factor linked to meat quality. Many intervention technologies including chlorine and EW treatment have been applied to reduce microbial contamination in meat and poultry (Ding and others 2010; Rahman and others 2012b, 2013). EW has been reported to be effective against populations of *L. monocytogenes*, *E. coli*, *S. typhimurium*, and *Clostridium jejuni* that are associated with chicken, pork, and other meat surfaces (Table 4). This can result in pathogen reduction ranging from 0.48 to 3.0 log CFU/g (8 to 10). Around the world, 40% of all the meat consumed is pork, followed by poultry meat and beef at 30% and 25%, respectively. Recently, Al-Holy and others (2015) reported the efficiency of AEW against *E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes* on raw trout skin, chicken legs, and beef surfaces. The treatment resulted in 1.5 to 1.6 log CFU/g reductions for *E. coli* O157:H7 and *S. typhimurium* in the inoculated foods. However, AEW exhibited

Table 3–Applications of EW in disinfecting various vegetables and fruits.

Microorganisms	Food commodities	EW type	Exposure time (min)	Reduction (log CFU)	[a]Chlorine conc. (ppm)	pH	ORP (mV)	Temperature	Reference
E. coli O157:H7	Broccoli	AEW	5	1.5/g	54.1	2.5	1108.6	24	Hung and others (2010)
	Cabbage	AlEW	5	2.6/g	NA	11-11.2	−830 to 850	50	Rahman and others (2010c)
	Kale	SAEW	3	2.3/g	5	6.3	898	40	Mansur and others (2015c)
	Oyster mushroom	LEW	3	1.8/g	5	6.2	500 to 520	23	Ding and others (2011a)
		StAEW	3	1.7/g	50	2.5	1100 to 1120	23	Ding and others (2011a)
	Spinach	LEW	3	2.4/g	5	6.3	520	23	Rahman and others (2010b)
		StAEW	3	2.6/g	50	2.5	1130	23	Rahman and others (2010b)
	Carrot	AlEW	3	2.6/g	NA	11.3	−810	50	Rahman and others (2011)
		LcEW	3	3.1/g	5-10	6.8-7.4	660 to 700	40	Forghani and others (2013a)
	Lettuce	StAEW	1	2.50.09/g	50	2.6	1100	35	Rahman and others (2010a)
		LcEW	1	2.4/g	5	6.3	500	35	Rahman and others (2010a)
		AEW	5	2.2/g	300	4	1150	30	Yang and others (2003)
	Iceberg lettuce	AEW	2	0.6/g	50	2.6	+1200	22	Keskinen and others (2009)
	Romaine lettuce	AEW	2	0.5/g	50	2.6	+1200	22	Keskinen and others (2009)
	Green onion	AEW	1	>5/g	37.5	2.0	NA	22	Park and others (2009a)
E. coli: 078	Cilantro	SAEW	5	1.9/g	19.5	5.8	809	25	Hao and others (2015)
		AEW	5	2.6/g	68.3	2.4	1127	25	Hao and others (2015)
		AlEW	5	0.5/g	NA	11.6	824	25	Hao and others (2015)
E. coli	Chinese celery	SAEW	15	2.7/g	21.4	5.8	931	20	Issa-Zacharia and others (2011)
		SAEW	15	2.8/g	21.4	5.8	931	20	Issa-Zacharia and others (2011)
	Lettuce	NEW	10	0.1/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
		NEW	5	1.8/g	89	8.5	733	20	Abadias and others (2008)
	Daikon sprout	SAEW	15	2.8	21.4	5.8	931	20	Issa-Zacharia and others (2011)
	Spinach	NEW	10	2.6/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
Salmonella spp.	Chinese celery	SAEW	15	2.8/g	22.1	5.6	931	20	Issa-Zacharia and others (2011)
	Lettuce	SAEW	15	2.9/g	22.1	5.6	931	20	Issa-Zacharia and others (2011)
		NEW	5	1.3/g	89	8.5	733	20	Abadias and others (2008)
	Daikon sprout	SAEW	15	2.9/g	22.1	5.6	931	20	Issa-Zacharia and others (2011)
L. monocytogenes	Cabbage	AlEW	5	2.6/g	NA	11 to 11.2	−830 to 850	50	Rahman and others (2010c)
	Kale	SAEW	3	2.6/g	5	6.3	898	40	Mansur and Oh (2015c)
	Oyster mushroom	LEW	3	1.4/g	5	6.2	500 to 520	23	Ding and others (2011a)
		StAEW	3	1.8/g	50	2.5	1100 to 1120	23	Ding and others (2011a)
	Spinach	LcEW	3	2.8/g	5	6.3	520	23	Rahman and others (2010b)
		StAEW	3	2.8/g	50	2.5	1130	23	Rahman and others (2010b)
	Spinach	NEW	10	>4/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
	Carrot	AlEW	3	2.7/g	NA	11.3	−810	50	Rahman and others (2011)
		StAEW	1	3.6/g	50	2.6	1100	35	Rahman and others (2010a)
	Lettuce	LEW	1	3.7/g	5	6.3	500	35	Rahman and others (2010a)
		AEW	3	2.2/g	50	2.3 to 2.7	1110 to 1200	25	Ding and others (2011b)
		NEW	10	2.2/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
		AEW	5	2.0/g	300	4	1150	30	Yang and others (2003)
	Green onion	AEW	1	>5/g	37.5	2.0	NG	22	Park and others (2009a)
S. Typhimurium	Oyster mushroom	LcEW	3	2.0/g	5	6.2	500 to 520	23	Ding and others (2011a)
		StAEW	3	2.0/g	50	2.5	1100 to 1120	23	Ding and others (2011a)
	Lettuce	StAEW	1	3.5/g	50	2.6	1100	35	Rahman and others (2010a)
		LcEW	1	3.6/g	5	6.3	500	35	Rahman and others (2010a)
		NEW	10	2.9/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
		AEW	5	1.7/g	300	4	1150	30	Yang and others (2003)
	Spinach	NEW	10	2.2/ml	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
	Green onion	AEW	1	>5/g	37.5	2.06	NA	22	Park and others (2009a)
B. cereus	Oyster mushroom	LcEW	3	2.0/g	5	6.2	500 to 520	23	Ding and others (2011a)
		StAEW	3	1.7/g	50	2.54	1100 to 1120	23	Ding and others (2011a)
S. aureus	Lettuce	StAEW	1	3.7/g	50	2.6	1100	35	Rahman and others (2010a)
		LcEW	1	3.9/g	5	6.3	500	35	Rahman and others (2010a)
		NEW	10	2.7/mL	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
	Spinach	NEW	10	3.4/mL	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
Enterococcus faecalis	Spinach	NEW	10	>4/mL	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
	Lettuce	NEW	10	2.6/mL	50	6.5 to 6.7	800 to 900	25	Guentzel and others (2008)
Enterobacteriaceae	Kale	SAEW	3	2.5/g	5	6.3	898	40	Mansur and Oh (2015c)
L. innocua	Lettuce	NEW	5	1.4/g	89	8.5	733	20	Abadias and others (2008)
Total aerobic bacteria	Cilantro	SAEW	5	2.5/g	19.5	5.8	809	25	Hao and others (2015)
		AEW	5	2.7/g	68.3	2.4	1127	25	Hao and others (2015)
		AlEW	5	1.0/g	NA	11.6	824	25	Hao and others (2015)
Coliform bacteria count		SAEW	5	1.6/g	19.5	5.8	809	25	Hao and others (2015)

(*Continued*)

Table 3–Continued.

Microorganisms	Food commodities	EW type	Exposure time (min)	Reduction (log CFU)	[a]Chlorine conc. (ppm)	pH	ORP (mV)	Temperature	Reference
	Cilantro	AEW	5	1.5/g	68.3	2.4	1127	25	Hao and others (2015)
		AlEW	5	0.5/g	NA	11.6	824	25	Hao and others (2015)
	Carrot	NEW	10	2.7/g	200	7.4	946.3	20	Lee and others (2014)
Total bacteria count	Cabbage	AlEW	5	3.0/g	NA	11 to 11.2	−830 to 850	50	Rahman and others (2010c)
	Kale	SAEW	3	2.7/g	5	6.3	898	40	Mansur and Oh (2015c)
	Lettuce	LcEW	3	2.0/g	5-10	6.8 to 7.4	660 to 700	40	Forghani and others (2013a)
Yeast and mold		SAEW	5	1.4/g	19.5	5.8	809	25	Hao and others (2015)
	Cilantro	AEW	5	1.6/g	68.3	2.4	1127	25	Hao and others (2015)
		AlEW	5	0.8/g	NA	11.6	824	25	Hao and others (2015)
	Cabbage	AlEW	5	2.7/g	NA	11 to 11.2	−830 to 850	50	Rahman and others (2010c)
	Kale	SAEW	3	1.7/g	5	6.3	898	40	Mansur and Oh (2015c)
	Oyster mushroom	LcEW	3	1.0/g	5	6.2	500 to 520	23	Ding and others (2011a)
		StAEW	3	1.0/g	50	2.5	1100 to 1120	23	Ding and others (2011a)
	Spinach	LcEW	7	0.3/g	5	6.3	520	23	Rahman and others (2010b)
	Carrot	AlEW	3	1.0/g	NA	11.3	−810	1	Rahman and others (2011)
Fruits									
A. acidoterrestris	Apple	NEW	5	<2/apple	48	7.5	770	20	Torlak (2014)
E. coli O157:H7	Strawberry	AEW	5	1.3/g	53.6	2.6	1059.5	24	Hung and others (2010)
	Tomato								
		AEW	1	>5/g	37.5	2.0	NA	22	Park and others (2009a)
		NEW	0.5	6.9/cm^2	86.4	8.1	771	23	Torlak (2014)
E. coli									
	Apple	AEW	30	2.1/g	98	2.9	1128	4	Graca and others (2011)
		NEW	30	1.5/g	49	8.3	753	4	Graca and others (2011)
	Tomato	NEW	0.5	6.6/cm^2	86.1	7.9	750	23	Torlak (2014)
S. Typhimurium									
	Tomato	AEW	1	>5/g	37.5	2.0	NA	22	Park and others (2009a)
L. monocytogenes	Tomato	NEW	0.5	6.7/cm^2	92.1	8.0	760	23	Torlak (2014)
		AEW	1	>5/g	37.5	2.0	NA	22	Park and others (2009a)
S. enteritidis	Tomato	NEW	0.5	6.2/cm^2	93.0	8.1	745	23	Torlak (2014)
L. innocua	Apple	AEW	30	1.9/g	98	2.9	1128	4	Graca and others (2011)
		NEW	30	1.5/g	49	8.3	753	4	Graca and others (2011)
S. choleraesuis	Apple	AEW	30	1.9/g	98	2.9	1128	4	Graca and others (2011)
		NEW	30	1.5/g	49	8.3	753	4	Graca and others (2011)
Total aerobic bacteria	Strawberry	SAEW	10	0.9/g	34.3	6.4	853.7	25	Ding and others (2015)
	Cherry tomato	SAEW	10	1.4/g	34.3	6.4	853.7	25	Ding and others (2015)
Yeast and mold									
	Strawberry	SAEW	10	0.9/g	34.3	6.4	853.7	25	Ding and others (2015)
	Cherry tomato	SAEW	10	1.1/g	34.3	6.4	853.7	25	Ding and others (2015)

AEW, acidic electrolyzed water; AlEW, alkaline electrolyzed water; LcEW, low concentration electrolyzed water; NA, not available; NEW, Neutral electrolyzed water; ORP, oxidation reduction potential; SAEW, slightly acidic electrolyzed water; StAEW, strong acidic electrolyzed water.

[a] Chlorine concentration represents available chlorine concentration (Cl_2, ^{-}OCl, and HOCl).

a lower bactericidal effect against *L. monocytogenes* (1.1 to 1.3 log CFU/g reduction). In another study, Venkitanarayanan and others (1999b) found that AEW effectively reduced the count of *E. coli* O157:H7, *S. enteritidis,* and *L. monocytogenes* regardless of the nature of microorganism (Gram positive or Gram negative). The antimicrobial effect of EW was more prominent at higher temperatures (>35) and longer holding times (15 min). Rahman and others (2013) studied the effectiveness of LcEW and SAEW against foodborne pathogens such as *E. coli* O157:H7 and *L. monocytogenes* on fresh pork. After 5 min of exposure, total reductions of 1.7 and 1.8 log CFU/g were recorded for LcEW and SAEW, respectively. Ding and others (2010) successfully modeled the growth of *E. coli* O157:H7 on beef at different temperatures ranging from 4 to 30 °C, when the beef was treated with AEW and SAEW. The results revealed that the specific growth rate of pathogens increased and lag time decreased when the temperature increased from 4 to 30 °C. Total reductions of 1.64 and 1.72 log CFU/g were recorded at 23 °C for AEW and SAEW treatments, respectively. These findings were further supported by the results of Wang and others (2012), who studied the growth of *L. monocytogenes* in pork and developed a model for treatment with LcEW as a function of temperature (4 to 30 °C). They reported that a higher specific growth rate and shorter lag time were obtained at higher temperatures with total reduction in pathogens by 1.7 log CFU/g. In the following year, Rahman and others (2012b) studied the effectiveness of slightly acidic low concentration electrolyzed water (SALcEW) treatment on fresh chicken breast meat inoculated with *L. monocytogenes* and *S. typhimurium*. After 10 min of treatment with SALcEW containing 10 ppm of active chlorine, total reductions of 2.32 and 1.91 log CFU/g were recorded for *L. monocytogenes* and *S. typhimurium*, respectively, at 23 °C. Further, poultry carcasses artificially contaminated with *C. jejuni* were treated with AEW, which resulted in reduction in the bacterial load by 0.6 to 3.0 log CFU/g (Park and others 2002a; Kim and others 2005).

Application of EW on seafood and fish

EW has already shown promising results as a sanitizer for seafood and fish, since its development for the prevention of foodborne outbreaks. The sushi industry in Japan has saved millions of dollars by washing raw fish with EW. Table 5 illustrates the effectiveness of EW on seafood and fish. Ozer and others (2006) examined the effect of AEW on salmon fillet at 35 °C. The population of *L. monocytogenes* Scott A was reduced by 0.5 to 1 log CFU/g, depending on the exposure temperature and time. In addition, the treatment of carp skin with AEW for 15 min reduced the microbial count by 2.8 log CFU/cm^2. In another study, the effect of AEW was found to be more pronounced for reducing *V. parahaemolyticus*

Table 4–Applications of EW against various microorganisms in poultry and meat.

Microorganisms	Food commodities	EW type	Exposure time (min)	Reduction (log CFU/g)	[a]Chlorine conc. (ppm)	pH	ORP (mV)	Temp.	Reference
E. coli O157:H7	Pork	LcEW	5	1.7	100.1	6.8	700	23	Rahman and others (2013)
		StAEW	5	1.8	50.2	2.5	1130	23	Rahman and others (2013)
	Beef	AEW	3	1.6	50	2.3–2.7	1110–1200	23	Ding and others (2010)
		SAEW	3	1.7	5	6.2	500–520	23	Ding and others (2010)
	Chicken	AEW	10	0.8	38	2.3	NA	22	Al-Holy and Rasco (2015)
	Beef	AEW	10	1.4	38	2.3	NA	22	Al-Holy and Rasco (2015)
L. monocytogenes									
	Pork	LcEW	5	1.7	100.1	6.8	700	23	Rahman and others (2013)
		StAEW	5	1.8	50.2	2.5	1130	23	Rahman and others (2013)
		LcEW	2	1.7	10	6.8	700	23	Wang and others (2012)
	Chicken meat	SALcEW	10	2.3	10	6.2–6.5	760–770	25	Rahman and others (2012b)
	x	StAEW	10	2.3	NA	2.5	1100–1120	25	Rahman and others (2012b)
	Chicken	AEW	10	1.1	38	2.3	NA	22	Al-Holy and Rasco (2015)
	Beef	AEW	10	1.3	38	2.3	NA	22	Al-Holy and Rasco (2015)
S. Typhimurium									
	Chicken meat	SALcEW	10	1.9	10	6.2–6.5	760–770	22	Rahman and others (2012b)
		StAEW	10	1.9	NA	2.5	1100–1120	22	Rahman and others (2012b)
	Chicken	AEW	10	1.5	38	2.3	NA	22	Al-Holy and Rasco (2015)
	Beef	AEW	10	1.4	38	2.3	NA	22	Al-Holy and Rasco (2015)
Total mesophiles									
	Chicken	AEW	10	2	38	2.3	NA	22	Al-Holy and Rasco (2015)
	Beef	AEW	10	2	38	2.3	NA	22	Al-Holy and Rasco (2015)
Yeast and mold									
	Pork	LcEW	5	0.9	100.1	6.8	700	23	Rahman and others (2013)
		StAEW	5	0.8	50.2	2.5	1130	23	Rahman and others (2013)
Total viable count									
	Pork	LcEW	5	1.2	100.1	6.8	700	23	Rahman and others (2013)
		StAEW	5	1.4	50.2	2.5	1130	23	Rahman and others (2013)
	Chicken meat	SALcEW	10	1.4	10	6.2–6.5	760–770	25	Rahman and others (2012b)
		StAEW	10	1.4	NA	2.5	1100–1120	25	Rahman and others (2012b)

AEW: acidic electrolyzed water; LcEW, low concentration electrolyzed water; NA, not available; ORP, oxidation reduction potential; SAEW, slightly acidic electrolyzed water, SALcEW, slightly acidic low concentration electrolyzed water; StAEW, strong acidic electrolyzed water.

[a] Chlorine concentration represents available chlorine concentration (Cl_2, ^{-}OCl, and HOCl).

than for reducing *E. coli* O157:H7 on tilapia skin (Huang and others 2006). Recently, Al-Holy and Rasco (2015) treated raw trout skin with AEW containing 38 ppm of active chlorine at pH 2.3 for 10 min. *E. coli* O157:H7, *S. typhimurium*, *L. monocytogenes,* and total mesophile count were reduced by about 1.5, 1.3, 0.9, and 0.3 log CFU/cm^2, respectively.

Application of EW in agriculture

Food safety and quality must be ensured during both preharvest and postharvest processing such as during handling, cleaning, and washing of raw materials, in pipelines and utensils, as well as during packaging. Farmers struggle to prevent crop diseases by using heavy equipment and notorious agricultural chemicals. In recent years, consumers are highly interested in obtaining high-quality safe produce. Meanwhile, the emergence of EW as a treatment method is an important landmark development, because it can be applied on-site by spraying or soaking methods, and helps prevent diseases and promotes growth with enhanced quality of produce.

The treatment of fresh produce with EW has been extensively studied (Hricova and others 2008). Several studies have shown the effectiveness of EW in reducing microbial count in functional food. Liu and others (2013) reported the antimicrobial efficacy and accumulation of gamma-aminobutyric acid (GABA) in brown rice by treating with SAEW. Furthermore, SAEW has been shown to not only exhibit antimicrobial potential, but also promote the growth of sprouts (Rui and others 2011). Recently, Li and others (2015) used SAEW treatment for microbial control during the germination of millet and for enhancing the accumulation of GABA. Treatment with a high concentration of available chlorine (30 ppm) produced strong anti-infection potential in germinated millet, in addition to promoting the accumulation of GABA by up to 21% (Al-Haq and others 2002). AEW has been shown to exhibit good antifungal effect against foliar diseases in plants. In addition, it is effective when used in postharvest dip treatment for peaches and pears (Buck and others 2002; Mueller and others 2003; Guentzel and others 2011). Guentzel and others (2011) further evaluated the efficacy of AEW at near neutral pH and based on their results, they suggested that AEW could be used for the disinfection of strawberry plants against *Bacillus cinerea* in the field. They also suggested that AEW can be used as a sanitizing solution in harvesting greenhouses, packing houses, on equipment, and in commercial facilities to manage or avoid *Monilinia fructicola* and *B. cinerea* infections. In another study, AEW with an ACC of 10 mg/L at near neutral pH (6.3 to 6.5) was found to inactivate *B. cinerea* conidia and minimize the incidence of grey mold on grape berries compared to the control used in the study (Guentzel and others 2010). Hopkins (2015) studied the antimicrobial efficacy of AEW on field peaches from the point of view of reducing the total count of microflora or inoculated *L. innocua*. Results of their study revealed significant reductions in both microflora and *L. innocua* populations on peaches. Hung and others (2010) reported that the treatment of broccoli and strawberries with AEW containing 23 to 100 ppm of active chlorine for 1 to 5 min resulted in significant reduction in the *E. coli* 0157:H7 count.

Table 5–Applications of EW in disinfecting seafood and fish.

Microorganisms	Food commodities	EW type	Exposure time (min)	Reduction (log CFU)	^{a}Chlorine conc. (ppm)	pH	ORP (mV)	Temperature	Reference
E. coli O157:H7	Trout fish	AEW	10	1.5/g	38	2.3	NA	22	Al-Holy and Rasco (2015)
E. coli	Tilapia	AEW	10	$1.7/\text{cm}^2$	120	2.4	1159	23	Huang and others (2006)
S. Typhimurium	Trout fish	AEW	10	1.5/g	38	2.3	NA	22	Al-Holy and Rasco (2015)
L. monocytogenes	Trout fish	AEW	10	1.2/g	38	2.3	NA	22	Al-Holy and Rasco (2015)
	Salmon	AEW	5	2.1/g	50	2.8	1080	RT	McCarthy and others (2012)
	Shrimp	AEW	5	1.9/g	21	2.3	1127	50	Xie and others (2012a)
V. parahaemolyticus									
	Tilapia	AEW	10	$3.8/\text{cm}^2$	120	2.4	1159	23	Huang and others (2006)
	Shrimp	AEW	5	3.1/g	21	2.3	1127	50	Xie and others (2012a)
		AEW	5	3.1/g	51	2.4	1163	50	Xie and others (2012b)
Morganella morganii									
		AEW	5	1.5/g	50	2.8	1080	RT	McCarthy and Burkhardt (2012)
	Salmon								
		AEW	120	$0.5/\text{cm}^2$	50	2.7	1211	RT	Phuvasate and others (2010)
Klebsiella pneumoniae	Salmon	AEW	120	ND	50	2.7	1211	RT	Phuvasate and Su (2010)
Proteus hauseri	Salmon	AEW	120	ND	50	2.7	1211	RT	Phuvasate and Su (2010)
Enterobacter cloacae	Salmon	AEW	120	$>0.7/\text{cm}^2$	50	2.7	1211	RT	Phuvasate and Su (2010)
Enterobacteraerogenes	Salmon	AEW	120	$0.9/\text{cm}^2$	50	2.7	1211	RT	Phuvasate and Su (2010)
Total mesophiles	Trout fish	AEW	10	2/g	38	2.3	NA	22	Al-Holy and Rasco (2015)
Total aerobic bacteria	Shrimp	AEW	5	1.4/g	21	2.3	1127	50	Xie and others (2012a)

AEW, acidic electrolyzed water; NA, not available; ND, not detected on direct plate; ORP, oxidation reduction potential; RT, room temperature.
^{a}Chlorine concentration represents available chlorine concentration (Cl_2, ^-OCl, and HOCl).

Application of EW on livestock

Many intervention technologies including antibiotics, vaccination, cleaning, and wiping have been introduced to reduce or prevent diseases in animal houses. Spraying or soaking is extensively used in advanced livestock breeding houses (Ferri and others 2010). Hao and others (2013a) reported the cleaning effectiveness of SAEW in the pH range of 5.0 to 6.5 in layer houses. Treatment with SAEW effectively decreased the survival rates of *Salmonella* spp. and *E. coli* by 21% and 16%, respectively. Hao and others (2013b) also reported on the potential applications of SAEW in swine barns. SAEW containing 300 ppm of active chlorine was flushed onto surfaces and sprayed within the whole swine barn. Spraying with SAEW significantly ($P < 0.05$) reduced the microbial count on the rail, floor, and walls of the swine barns. In another study, Hao and others (2014) reported the inactivation of airborne bacteria in a commercial layer house in northern China by treatment with SAEW. The results showed that the airborne microorganism and fungi counts were reduced by 4.85 and 3.45 log CFU/m^3, respectively, after 30 min of exposure to SAEW. Recently, Zheng and others (2014) studied the efficacy of SAEW in reducing airborne culturable bacteria and particulate matter levels in hen houses. The results of the study showed the inactivation of airborne culturable bacteria attached to particulate matter. In summary, research has revealed EW to be a potential antimicrobial agent for reducing microbial presence in layer houses, swine barns, slaughter house, and animal breeding houses.

Application of EW on contact surfaces and tools in the food industry

Bacterial cross-contamination can occur from the preparation equipment and tableware during food processing. Improper cleaning and sanitization of the tools used in the food industry was reported as a serious problem by the U.S. Food and Drug Administration (FDA 2009). Thus, cleaning and sanitization of these tools should be optimized to ensure food safety. In this context, EW has been employed as a novel sanitizing agent to reduce the bacterial count on food contact surfaces to acceptable levels. The effectiveness of NEW or AEW has been examined by several researchers and they have been recommended as novel food contact surface sanitizers (Izumi 1999; Deza and others 2005; Deza and others 2007). The use of AEW solution effectively reduced the bacterial populations on metal and plastic surfaces, as well as on disposable fabric wipes (Lee and others 2007a,b). Handojo and others (2009) used NEW and AEW to achieve antimicrobial effect against *E. coli* K-12 and *S. epidermidis* inoculated onto stainless steel cutlery, ceramic plates, and drinking glasses (Table 6). Their results indicated that treatment with AEW and NEW reduced the bacterial populations by more than 5 log CFU per tableware item for all the treatment conditions. In another study, the disinfection efficacy of NEW on cutting boards (hard and bamboo boards) inoculated with *E. coli* K-12 and *L. innocua* was examined. Significant reduction in foodborne pathogens was recorded, regardless of the type of cutting board sample treated (Monnin and others 2012).

Application of EW in hospitals

The increasing number of diagnostic examinations around the world increases the possibility of hard surface contamination in hospitals with potentially dangerous microorganisms from infected patients. These surfaces represent possible sources of infection for medical staff and other patients (Chaoui and others 1995; Grabsch and others 2006; Buerke and others 2012). Pintaric and others (2015) reported the potential use of EW in diagnostic rooms and equipment such as computer tomographs and magnetic resonance imaging scanners. Their results revealed that treatment with AEW effectively reduced the total bacterial count by about 50% to 80% without any detrimental effect. Gao and others (2001) evaluated the effect of AEW on gastroscope immersed in gastric juice containing hepatitis B surface antigen (HBsAg). After 1 min of treatment with AEW, the HBsAg content was shown to be negative. Fungal species that are responsible for hospital infections include *Aspergillus* species, *Candida albicans*, and other *Candida* species. Ünal and others (2014) reported the inactivation effect of AEW on all yeasts and fungi including *C. albicans*, *Candida parapsilosis, Candida tropicalis, Candida krusei, Candida glabrata, Candida lusitaniae, Trichosporon* spp., and molds; as well as *A. flavus*, *Aspergillus fumigatus*, and *Aspergillus niger* isolated from clinical samples. Recently, Stewart and others (2014) evaluated EW treatment for the disinfection of cleaning near-patient sites in wards housing elderly patients in a district general hospital in Scotland. The aerobic

Table 6–Applications of EW against various microorganisms on different food contact surfaces.

Microorganisms	Food surfaces	EW type	Exposure time (min)	Reduction (log CFU)	[a]Chlorine conc. (ppm)	pH	(mV)	Temperature	Reference
E. coli K-12	Plate	NEW	0.1	>5/item	100	7.4	NA	24	Handojo and others (2009)
	Spoons	NEW	0.1	>6/iem	100	7.4	NA	24	Handojo and others (2009)
	Forks	NEW	0.1	>5.5/item	100	7.4	NA	24	Handojo and others (2009)
	Knives	NEW	0.1	>6.5/item	100	7.4	NA	24	Handojo and others (2009)
	Drinking glasses	NEW	0.1	>6/item	100	7.4	NA	24	Handojo and others (2009)
	Bamboo board	NEW	0.1	4.3/cm^2	120	7.0	799.6	23	Monnin and others (2012)
	Hardwood board	NEW	0.1	3.8/cm^2	120	7.0	799.6	23	Monnin and others (2012)
S. epidermidis	Plate	NEW	0.1	>5/item	100	7.4	NA	24	Handojo and others (2009)
	Spoons	NEW	0.1	>6.5/item	100	7.4	NA	24	Handojo and others (2009)
	Forks	NEW	0.1	>6/item	100	7.4	NA	24	Handojo and others (2009)
	Knives	NEW	0.1	>6.6/item	100	7.4	NA	24	Handojo and others (2009)
	Drinking glasses	NEW	0.1	>6.9/item	100	7.4	NA	24	Handojo and others (2009)
L. innocua	Bamboo board	NEW	0.1	4/cm^2	120	7.0	799.6	23	Monnin and others (2012)
	Hardwood board	NEW	0.1	4/cm^2	120	7.0	799.6	23	Monnin and others (2012)
L. monocytogenes	Shrimp meat nitrile gloves	AEW	5	1.6/cm^2	40	2.6	1125	21	Liu and others (2006)
	Natural rubber latex gloves	AEW	5	2.4/cm^2	40	2.6	1125	21	Liu and Su (2006)
	Natural latex gloves	AEW	5	1.9/cm^2	40	2.6	1125	21	Liu and Su (2006)
	Latex (disposable) gloves	AEW	5	2.5/cm^2	40	2.6	1125	21	Liu and Su (2006)
	Nitrile (disposable) gloves	AEW	5	3.8/cm^2	40	2.6	1125	21	Liu and Su (2006)
Enterobacter aerogenes	Stainless steel	AEW	5	>5.4/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
	Glazed ceramic tile	AEW	5	>4.2/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
Enterobacter cloacae	Stainless steel	AEW	5	3.1/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
	Glazed ceramic tile	AEW	5	>2/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
Klebsiella pneumoniae	Stainless steel	AEW	5	>1.7/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
	Glazed ceramic tile	AEW	5	>0.9/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
Morganella morganii	Stainless steel	AEW	5	>3.4/cm^2	50	2.7	1211	RT	Phuvasate and Su (2010)
	Glazed ceramic tile	AEW	5	ND	50	2.7	1211	RT	Phuvasate and Su (2010)
Proteus hauser	Stainless steel	AEW	5	ND	50	2.7	1211	RT	Phuvasate and Su (2010)
	Glazed ceramic tile	AEW	5	ND	50	2.7	1211	RT	Phuvasate and Su (2010)
Total bacteria count	Cafeteria table	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Water fountain	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Sink faucet	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Bathroom door	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Phone booth	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Cafeteria food line	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Keyboard	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Cafeteria tray return area	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Air vent cover	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)
	Library checkout counter	NEW	10	5-6/mL	278–310	6.3	872–885	25	Guentzel and others (2008)

AEW, acidic electrolyzed water; NA, not available; ND, not detected on direct plate; NEW, neutral electrolyzed water; ORP, oxidation reduction potential; RT, room temperature.

[a]Chlorine concentration represents available chlorine concentration (Cl$_2$, $^-$OCl, and HOCl).

bacterial count was reduced by 2.65 orders of magnitude, whereas the total methicillin-susceptible *S. aureus* and methicillin-resistant *S. aureus* (34 isolates) populations decreased by 71%. Hospital liquid infectious waste is one of the major causes of water contamination. A study on the treatment of waste water effluents containing urine and blood from diagnostic labs in hospitals by AEW treatment at various pH values has been reported. Treatment efficiencies of 96.15% and 84.81% were obtained for urine and blood, respectively (Sarwar and others 2011). Another study was carried out to disinfect 150 disposable tubes used for diagnostic purposes using AEW, and the results indicated successful disinfection efficacy of AEW (Tateda and others 2011).

Hurdle Enhancement of EW with Other Treatments

The application of EW on food products is a promising technique for reducing the total count of pathogenic and spoilage bacteria. However, at the same time it has shown some undesirable effects on the organoleptic quality and nutritional value of food (Rahman and others 2010c, 2011, 2012b; Tango and others 2015). To overcome these limitations associated with EW, a combination of 2 or more preservative and sanitizing technologies in low quantities could be used. For example, the combination of AEW, AlEW, and mild heat has been shown to have a better bactericidal effect on lettuce than individual treatment (Koseki and others 2004; Koseki and Isobe 2007). In another study, Hao and others (2015) investigated the combined sanitizing effects of AlEW and AEW on fresh-cut cilantro. Their results revealed significantly reduced microbial count by the combined treatment compared to treatment by the individual methods.

Many studies have shown remarkable reduction of microbial count in a variety of food products treated with a combination of EW and organic acids (Park and others 2004; Rahman and others 2013; Mansur and others 2015b; Tango and others 2015). When the combination of citric acid and AIEW was investigated on

Table 7–Combination of EW with other treatment procedures to decontaminate food.

Combination type	Food product	Microorganisms	Reduction Reduction (log CFU/g)	Shelf-life	Reference
AlEW 2.5 min- AEW 2.5 min	Fresh-cut cilantro	Aerobic bacteria	3.73	–	Hao and others (2015)
Mildly heated (50 °C) AlEW – chilled (4 °C)AEW	Lettuce	*E. coli* O157:H7	3.0–4.0	–	Koseki and others (2004)
		Salmonella	3.0–4.0		
Mildly heated (50 °C) AlEW – mild heated (50 °C)AEW	Shrimp	*V. parahaemolyticus*	5.4	–	Xie and others (2012b)
1% CA + AlEW at 50 °C	Shredded carrots	Aerobic bacteria	3.71	Enhanced shelf-life extension	Rahman and others (2011)
		Yeast and fungi	3.69		
		L. monocytogenes	3.97		
		E. coli O157:H7	4.0		
1% CA + AlEW at 50 °C	Cabbage	Aerobic bacteria	3.98	–	Rahman and others(2010c)
		Yeast and mold	3.45		
		L. monocytogenes	3.99		
		E. coli O157:H7	4.19		
1% CA + AlEW at 40 °C	Brown rice	*B. cereus* vegetative cell	4.21	–	Park and others (2009b)
		B. cereus spore	3.57		
Sonication – LcEW at 40 °C	Lettuce	Aerobic bacteria	2.6	Enhanced shelf-life extension	Forghani and others (2013a)
		E. coli O157:H7	3.18		
Sonication + SAEW	Fresh-cut kale	*E. coli* O157:H7	3.32	–	Mansur and Oh (2015c)
		L. monocytogenes	3.11		
		Aerobic bacteria	3.97		
		Enterobacteriaceae	3.66		
		Pseudomonas spp.	3.62		
		Yeast and mold	>3.24		
Sonication + SAEW	Fresh-cut kale	*L. monocytogenes*	3.0	Enhanced shelf-life extension	Mansur and Oh (2015a)
SAEW + 0.5% FA at 40 °C	Beef	Aerobic bacteria	3.67	Enhanced shelf-life extension	Tango and others (2014)
		S. aureus	2.68		
		E. coli O157:H7	3.01		
		L. monocytogenes	2.84		
		S. Typhimurium	2.70		
LcEW + 3% CaL	Pork	Aerobic bacteria	2.2	Enhanced shelf-life extension	Rahman and others (2013)
		Yeast and mold	1.57		
		L. monocytogenes	3.17		
		E. coli O157:H7	3.0		
UV-C + EW	Date palm fruit	–	–	Enhanced shelf-life extension	Jemni and others (2014)

–, no data; AEW, acidic electrolyzed water; AlEW, alkaline electrolyzed water; CA, citric acid; CaL, calcium lactate; FA, fumaric acid; LcEW, low concentration electrolyzed water; SAEW, slightly acidic electrolyzed water; UV-C, ultraviolet-C light.

cereal grains and fresh cut harvest, a synergistic antimicrobial effect was observed, which resulted in reduction in background flora as well as foodborne pathogens (Park and others 2004; Rahman and others 2010c, 2011). In another study conducted by Rahman and others (2011), 1% citric acid was applied in combination with AlEW for the treatment of shredded carrots, in an attempt to increase their shelf life. The combined treatment with citric acid and AlEW immediately reduced the total bacterial count. In order to enhance the freshness and hygienic quality of the carrots and increase their storage time under refrigeration, sanitizing by the citric acid/AlEW combination would be an effective method. Treatment with the same combination yielded similar results for cabbage (Rahman and others 2010c). Among all the organic acids that are utilized as antimicrobial agents on meat (such as lactic acid and acetic acid), fumaric acid (FA) has been shown to exhibit strong bactericidal effects (Podolak and others 1995, 1996). Treatment with the combination of SAEW and FA has been shown to prolong the shelf life of beef and pork with greater bactericidal effect as compared to individual treatments (Mansur and others 2015b; Tango and others 2014). The meat industry has been using salts of organic acids such as calcium lactate, owing to their ability to increase flavor, prolong shelf life, and improve the microbiological safety of the products (Lawrence and others 2003; Naveena and others 2006; Selgas and others 2009). Moreover, the palatability and tenderness of meat products can be maintained by this method, owing to the inclusion of calcium (Lawrence and others 2003). Rahman and others (2013) also noted that when pork was treated with a combination of LcEW and calcium lactate at a cold temperature (4 °C), the shelf life increased by 6 d.

Furthermore, EW in combination with other chemical and physical sanitizing techniques such as ozone, chitosan, heat treatment, and sonication has been evaluated for its sanitizing effect on a variety of food products (Koseki and Isobe 2007; Mansur and others 2015a; Mansur and Oh 2015c; Sagong and others 2011). Xu and others (2014) studied the effect of chitosan in combination with AEW on the quality of fish during refrigerated storage. The results revealed that better color, sensory characteristics of the fish, and texture were obtained as a result of treatment with the AEW and chitosan combination. The shelf life of American shad fillets was also found to increase by 9 to 10 d because of this treatment under refrigerated storage. Recently, Shiroodi and others (2016) studied the effect of AEW/mild heat combination in cold-smoked Atlantic salmon (*Salmo salar*) against *L. monocytogenes*. Their results showed that AEW in combination with mild heat at 40 °C reduced *L. monocytogenes* count by 2.85 log CFU/g and did not adversely affect the texture and sensory properties of cold-smoked salmon. Previously, Xie and others (2012b) also studied the AEW/mild heat combination against *V. parahaemolyticus* on shrimp. Their results showed a 3.1 log CFU/g reduction of *V. parahaemolyticus* cells on shrimp by treatment with AEW and mild heat (50 °C). The order of temperature arranged according to the bactericidal activities of AEW was 50 °C > 20 °C > 4 °C.

The combined treatment procedures have been compared with individual treatments and the results show that the combined treatment procedures may impart a preservative effect or even synergistic bactericidal effect. Therefore, it can be concluded that the food industry would greatly benefit by adopting treatment procedures involving combinations of EW and other treatments (Table 7), as a form of post-harvest intervention method. Such treatments would enhance the shelf life of produce and microbiological safety will be improved.

Future Perspectives

Jerome (2014) considered EW as a potential future sanitizer and cleaner for the food industry. EW has been approved by U.S. regulators as a replacement for harmful chemicals and as a green and sustainable solution for use at home and in the industry. While EW has been used in various sectors in Russia and Japan for several decades, it is slowly getting acceptance in the US and other countries (Dickerson 2009).

Recently, a continuously growing trend for the commercialization of EW around the globe is being observed. Keeping in view the importance of EW, many companies have been established and are producing EW. Examples of such companies include envirolyte®, KEWS, RVD Corporation, EcoLogic Solutions Inc., Viking pure™, and eWater Advantage, which are based in Estonia, South Korea, Latvia, and U.S.A. These companies claim to produce 100% pure, eco-friendly, nontoxic, and less expensive EW for domestic and industrial use (VikingPure 2015, KEWS 2015, Envirolyte 2015, eWater Advantage 2015). Another U.S.-based company, EAU Technologies Inc., completed a trial by using EW with a leading international beverage bottling company in September, 2009, which aided the approval of the use of EW technology as a sanitation process for CIP (Clean-in-Place) applications. EW produced by EAU Technologies is marketed under the brand-name Empowered Water™ and is an environmentally friendly and highly effective solution for CIP applications for industrial use. In particular, in the food industry, CIP applications are used to clean stationary equipment during a product change over and system start-up (EAU 2009).

There are diverse opinions on the sanitizing applications and regulations of EW in different sectors around the globe. In the European Union (EU), EW can only be applied to “drinking water” and its use on food products such as meat and fish is not permitted, because of its properties of protein inactivation (Stephan 2016). However, in the United States, it is used for drinking, cleaning, and sanitizing purposes. Recently, the U.S. Department of Agriculture (USDA) approved the application of EW in organic products (USDA 2015). In the near future, most of the industry is likely to start using EW, owing to its benefits. The EW solution is relatively simple in composition, and once it gets exposed to water, it gets diluted and its sanitizing efficacy drops. Humans are also unaffected by exposure to EW, as long as the eyes are not exposed and it is not orally ingested. Many chemical industries do not possess sufficient knowledge on EW, and more advertisement is required to introduce it to the industry. There is a good future for EW, and over the next 10 y, most of the food plants will start using EW, owing to its benefits (Ovissipour 2016).

Conclusions

EW exhibits strong bactericidal, fungicidal, and virucidal effects in various sectors such as medicine and dentistry as well as on fruits, vegetables, seafood, eggs, poultry, utensils, agriculture, raw meat, and carcasses. However, EW with very low pH (≤2.7) is corrosive in nature and affects the organoleptic properties of some foods, which limit its use. With the development of newer types of EW such as SAEW and SAlEW, some of these issues have been solved. The application of combination of multiple techniques has shown advantages over individual treatment in terms of synergistic microbial reduction, enhanced shelf life, and food quality maintenance. Various factors in addition to the physiochemical properties of EW are found to govern the efficacy of EW such as water temperature, ACC, ORP, pH, type of electrolyte, flow rates of water and electrolyte, storage conditions, and concentration of salts, which need to be monitored during its production and applications. Further, the bactericidal activity of EW is also influenced by the presence of organic matter, water hardness, and pollutants in the product. Therefore, an advanced and dynamic EW production system that is capable of overcoming all the current limitations can be developed through further research in the field. These may include procedures for expanding the usage of EW in food processing settings and the application in HACCP and Sanitation SOP systems.

Acknowledgments

This study was supported by High Value-added Food Technology Development Program (314059-3), Ministry of Agriculture, Food and Rural Affairs, South Korea. Authors are grateful to Professor Dr. Roger Stephan, Director, Institute for Food Safety and Hygiene, University of Zurich, Zürich, Switzerland, and Professor Dr. Mahmoudreza Ovissipour, Professor, Department of Biological Systems Engineering, Washington State University, Pullman, USA, for their valuable statements regarding the future of EW in the EU and US, respectively.

Authors' Contributions

S.M.E. Rahman and D.-H. Oh contributed substantially to the conception and design of this review article. S.M.E. Rahman and I. Khan compiled data and drafted the manuscript. D.-H. Oh critically revised the work and approved the final version for publication.

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