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Review Article

Application of Slightly Acidic Electrolyzed Water as a Potential Sanitizer in the Food Industry

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The food industry has extensively explored postharvest microbial control, seeking viable technologies to ensure food safety. Although numerous chlorine-based commercial sanitizers serve this purpose, many are plagued by constraints such as instability and diminished disinfectant efficacy. These issues arise from exposure to organic matter in wash water, light, or air. As an innovative and promising alternative, slightly acidic electrolyzed water (SAEW) has emerged, captivating attention for its robust sterilization potential and eco-friendliness in agricultural and food sectors. SAEW generated via electrolysis of a diluted hydrochloric acid (HCl) solution with concentrations ranging from 2 to 6% or aqueous solution of sodium chloride (NaCl) in a nonmembrane electrolytic chamber is reported to possess equivalent antimicrobial properties as strong acidic electrolyzed water (StAEW). In contrast to traditional chlorine sanitizers, SAEW leaves less chlorine residue on sanitized foods such fresh-cut fruit and vegetables, meat, poultry, and aquatic products due to its low available chlorine concentration (ACC). Its near neutral pH of 5 to 6.5 not only renders it environmentally benign but also mitigates the production of chlorine gas, a contrast to low pH conditions seen in StAEW generation. The bactericidal effect of SAEW against various strains of foodborne pathogens is widely believed and accepted to be due to the combined action of high oxidation-reduction-potential (ORP) reactions and undissociated hypochlorite/hypochlorous acid (HOCl). Consequently, a burgeoning interest surrounds the potential of SAEW for sanitation in the food industry, offering an alternative to address shortcomings in sodium hypochlorite solutions and even StAEW. It has been hypothesized from a number of studies that SAEW treatment can increase the quality and nutritional value of harvested fruits, which in turn may enhance their ability to be stored. Therefore, SAEW is not only a promising sanitizer in the food industry but also has the potential to be an efficient strategy for encouraging the accumulation of bioactive chemicals in plants, especially if it is used extensively. This review encapsulates the latest insights concerning SAEW, encompassing its antimicrobial effectiveness, sanitization mechanism, advantages vis-à-vis other sanitizers, and plausible applications across the food industry.

1. Introduction

Ensuring food safety remains a paramount concern within the food industry, necessitating the utilization of an effective and appropriate sanitization method. Among the array of disinfection techniques, a burgeoning approach has emerged, centered on the implementation of electrolyzed water (EW) as a novel and alternative means of sanitation in the food sector, characterized by its dual benefits of environmental safety and user well-being [1]. The inception of electrolyzed water dates back to its initial application in food processing within the Japanese soda industry in 1980 [1–3].

Through electrolytic processes, a dilute sodium chloride solution undergoes dissociation, resulting in the formation of acidic electrolyzed water (AEW). AEW is of two distinct acidic variants, namely, strong acidic electrolyzed water (StAEW, pH 2-3) and slightly acidic electrolyzed water (SAEW, pH 5–6.5). The latter, slightly acidic electrolyzed water (SAEW), has been refined over two decades by Japanese enterprises [4], obtaining official recognition as a food additive by the Japanese Ministry of Health, Labor, and Welfare in 2002, as well as securing authorization as a control agent from the Ministry of Agriculture, Forestry, and Fisheries and the Ministry of the Environment in 2014 [4]. In contrast to StAEW, which arises from the electrolysis of a 2% sodium chloride aqueous solution, SAEW is derived from electrolyzing a diluted hydrochloric acid (HCl) solution, typically ranging from 2% to 6%, within an electrolytic cell devoid of a diaphragm [5–7].

The ascendancy of SAEW in Japan's realm of food sanitation is swiftly advancing, positioning it as a prospective alternative to antimicrobial detergents and an ecologically friendly disinfecting agent [8]. The distinguishing attribute of SAEW is its capacity to mitigate the deleterious implications of chlorine residuals on human and environmental well-being [9]. While StAEW finds application across various agricultural domains such as vegetable sterilization, food processing, and domestic kitchens for food material and utensil disinfection, SAEW's industry-level utilization has remained comparatively limited. Unlike StAEW, with its pH within the range of 2.0 to 3.0, SAEW boasts a pH of 5 to 6.5 and exhibits substantial antibacterial potency attributed to its elevated hypochlorous acid (HOCl) concentration, concurrently resulting in reduced negative impacts on human health and the environment [7, 10].

SAEW's superiority over StAEW is multifaceted, including heightened preservative efficacy during storage [11–13], minimal pH, color, and appearance alteration of fresh-cut vegetables [14], as well as reduced contributions to equipment corrosion and skin irritation in comparison to StAEW [15]. In addition, SAEW sidesteps issues such as phytotoxicity in plants and safety concerns stemming from chlorine gas emissions [16], positioning it as a promising avenue for application, particularly within the fresh and ready-to-eat fruit and vegetable sector. Consequently, SAEW has gained substantial traction as a preservative within the food industry [3, 17, 18].

Although StAEW has limitations such as loss of its bactericidal activity due to chlorine (Cl_2) loss [19] hindering its postproduction storage which necessitates the on-site production and application, the fact remains, however, that StAEW exhibits potent bactericidal and virucidal effects, as well as moderate fungicidal properties [1]. In addition to StAEW, chemical sanitizers such as chlorine and its derivatives are commonly utilized in the food industry to produce food that is both high-quality and microbiologically safe for human consumption [20], hydrogen peroxide [21], ozone [22], and organic acids [23]. However, due to the possibility for the development of carcinogenic halogenated disinfection byproducts, which pose a threat to human and environmental health, certain chemical sanitizers are prohibited in a number of European nations and other countries [24–26]. Although chlorine and chlorine derivatives are frequently employed as sanitizers in the fresh-cut food business to reduce microbial contamination, they pose a health concern and should be avoided. Furthermore, the chlorine solution can cause irritation to the skin and lungs. In addition, its effectiveness diminishes when exposed to air, light, and metals [27]. Trihalomethanes (THMs), chloroform, and chlorophenols are all byproducts that pose a health risk due to their potential mutagenicity and classification as probable human carcinogens by the US Environmental Protection Agency (EPA) [28].

On the other hand, unlike StAEW that is reported for its storage unstability, SAEW is known to exhibit greater stability during storage due to a considerable reduction in chlorine loss at pH 5–6.5 5. As a result, the factor responsible for the bactericidal effect of SAEW is more stable compared to the similar factor in StAEW [7, 10, 29, 30]. The fundamental properties and effectiveness against microorganisms of electrolyzed water (StAEW and SAEW) are significantly affected by the storage conditions. This is due to the degradation of the main antimicrobial component (HOCl) and the evaporation of Cl_2, which can be greatly influenced by the storage conditions, especially when exposed to open or light conditions. For instance, Rahman et al. [31] compared the ACC of low-concentration electrolyzed water (LcSAEW: 10 mg/L, pH range of 6.8–7.4) exposed to open and closed conditions and found that under open-dark settings, the ACC of LcSAEW dropped from 10 to 0 mg/L in just 7 days, compared to 21 days under closed-dark conditions. SAEW (ACC:20 mg/L) was evaluated for changes in fundamental properties (pH, ORP, and ACC) during storage in open and closed glass bottles at room temperature in both light and dark settings [32]. The findings indicated that storing EW in a closed-dark container was a more favorable setting. According to a study conducted by Len et al. [33], the depletion of chlorine in electrolyzed water (EW) when exposed to an open environment can be attributed to the evaporation of chlorine and its subsequent interaction with the atmosphere. This finding was further supported by the research conducted by Xuan and Ling [32]. The chlorine underwent self-decomposition at a significantly greater rate when held under open conditions, as opposed to closed ones.

While the efficacy of SAEW in microbial inactivation in foods has been demonstrated, its utilization is vulnerable to interference caused by organic matter, leading to a reduction in disinfection effectiveness [34]. Hence, the recent investigation conducted by Zhao et al. [35] has explored the combination of SAEW with other disinfection techniques as a potential solution to address this issue. Among them, combination of SAEW with ultraviolet (UV) light (SAEW + UV) has demonstrated a remarkably potent germicidal action. An investigation by Zhang et al. [36] showed that the combination treatment of SAEW and UV has shown a greater antimicrobial efficacy against *Staphylococcus aureus* than the individual treatments of UV or SAEW alone. Furthermore, the antimicrobial impact was observed to intensify with both time and ACC. Recent reports have highlighted several limitations of SAEW, such as water hardness, which is thought to have a significant impact on its physical qualities and sanitization performance. Nevertheless, SAEW is still being proposed as a potential novel sanitizer for use in agriculture and food processing [37]. Therefore, the agriculture and food industries should pay attention to SAEW as a revolutionary technology with significant potential for sterilizing.

2. Production of Slightly Acidic Electrolyzed Water

Slightly acidic electrolyzed water (SAEW) is created from the electrolysis of a combination of diluted hydrochloric acid solution HCl (2–6%) in a chamber cell without a membrane and tap water in an electrolytic cell containing both cathode (Ti) and anode (IrO2) [38]. SAEW can also be made by electrolysis of dilute electrolyte of NaCl in an electrolysis chamber without the diaphragm [37, 39, 40]. The SAEW generator comprises an electrolytic cell with anode and cathode electrodes that are without a separating membrane between them [41–43]. Figure 1 shows a schematic depiction of the SAEW generating equipment and the compounds that are generated through electrolysis.

The basic chemical reactions at the anode and cathode can be summarized below. At the anode side,

$$2Cl^- \longrightarrow Cl_2\uparrow + 2e^- \tag{1}$$

$$Cl_2 + H_2O \longrightarrow HOCl + H^+ + Cl^- \tag{2}$$

At the cathode side,

$$H^+ + 2e^- \longrightarrow {}^{H2}\uparrow \tag{3}$$

Electrolysis causes the dissociation of diluted hydrochloric acid in water, resulting in the formation of negatively charged chlorine ions (Cl^-) and positively charged hydrogen ions (H^+). The negatively charged ions (Cl^-) migrate towards the anode to give up electrons and become chlorine gas (Cl_2) that dissolves in water to create hypochlorous acid also known as undissociated hypochlorite (HOCl), H^+, and Cl^- ions. Positively charged hydrogen (H^+) ions move to the cathode to take up electrons and become hydrogen gas (H_2) that evaporates. As a result of this process, unlike StAEW, this solution dissociates into only one type of solution (SAEW), with near neutral pH (5.0–6.5) and high oxidation–reduction potential (ORP, 800–900 mV), and contains available chlorine concentration (ACC) of 10–30 mg/L in the form of hypochlorous acid. In StAEW generation, a solution of sodium hydroxide has two forms of electrolyzed water: acidic electrolyzed water (AEW) and basic electrolyzed water (BEW) [32, 44].

3. SAEW-Producing Equipment

Currently, there are various SAEW-producing devices accessible in the market, and generators manufactured by well-known companies have been widely embraced by consumers. Such devices include MIOX (Albuquerque, NM, United States), AQUACIDO NDX-250KMS (OSG Company Ltd., Osaka, Japan), Water God HD-240L (Shanghai, China), and APIA series (Japan) [1, 29, 45]. Currently, Japan is widely recognized as the principal manufacturer of such machines with the most common machines being the HOCL series (Institute of Slightly Acidic Electrolyzed Water, Inc., Kanagawa, Japan), Purestar series (Morinaga Engineering Co., Ltd, Kanagawa, Japan), and Apia series (Hokuty Co., Ltd, Kanagawa, JAPAN). Other common SAEW generators manufactured by reputable companies in different countries are summarized in Table 1.

The properties of SAEW can be significantly influenced by the chlorine concentration, amperage, voltage, flow rate, and water hardness [51], and each of these generators is made with specific technical parameters to meet the requirements. For research purposes, the SAEW generator could be self-developed and used to study the effect of SAEW [10, 52, 53]. For instance, Forghani and Oh [54] used a self-developed device to generate SAEW at a setting of 2.9 A and 24 V. The production capacity ranges from 60 l/h to 10,000 l/h indicating that the technology can be used at the laboratory, household, and industrial levels to produce safe food. Slightly acidic electrolyzed water of the desired 10–30 mg/L ACC or even more is produced by suitably adjusting the amount of supply of hydrochloric acid, amount of supply of water, and current, which is performed automatically in most models, and could be manually preset by an operator in some models.

4. Antimicrobial Properties of Slightly Acidic Electrolyzed Water

The prominent properties (features) of SAEW are shown in Table 2. Physicochemical properties of SAEW as reported by most researchers include a near-neutral/slightly acidic pH of 5–6.5, high oxidation-reduction potential (ORP; ≥800 mV), and low available chlorine concentration (ACC; 10–30 mg/l) [16, 61, 72]. Hypochlorous acid (HOCl), also referred to as undissociated hypochlorite, exhibits the most potent bactericidal activity against a wide spectrum of microbes among all forms of free available chlorine. In aqueous solutions, the equilibrium between HOCl and the hypochlorite ion (OCl-) is pH dependent with the concentration of HOCl increasing as pH decreases (Figure 1). At the pH 5.0–6.5, the active form of chlorine compounds in SAEW is mainly HOC (>95%) and 5% is OCl- and traces of Cl_2 as shown in Figure 2 [56, 73]. Both HOCl (undissociated hypochlorite/electrically neutral) and dissociated hypochlorite (OCl-/electrically negative) have microbial disinfecting behavior. However, undissociated hypochlorite (HOCl) is considered the most microbicidal form of chlorine. The cell wall of pathogenic microbes has an inherent negative charge. As such, the uncharged species (HOCl) is freely permeable across the plasma membrane of microorganisms and thus can enter the cell. HOCl is important in sanitization more than other forms because the chlorine in the Cl_2 form can volatilize as pointed out by Cui et al. [55], and the efficacy against microorganisms can be lost. Therefore, a neutral pH is an advantageous property for preventing the evaporation of chlorine and keeping the concentration of HOCl stable. With this property and at the same concentrations, SAEW's sanitizing activity is 80 times more than that of OCl-, making it the most effective germicide form of chlorine in solutions [57].

Hence, the application of SAEW with a pH close to neutral holds great potential due to its ability to mitigate human health and safety concerns arising from the release of Cl_2 gas, minimize surface corrosion, and restrict phototoxic

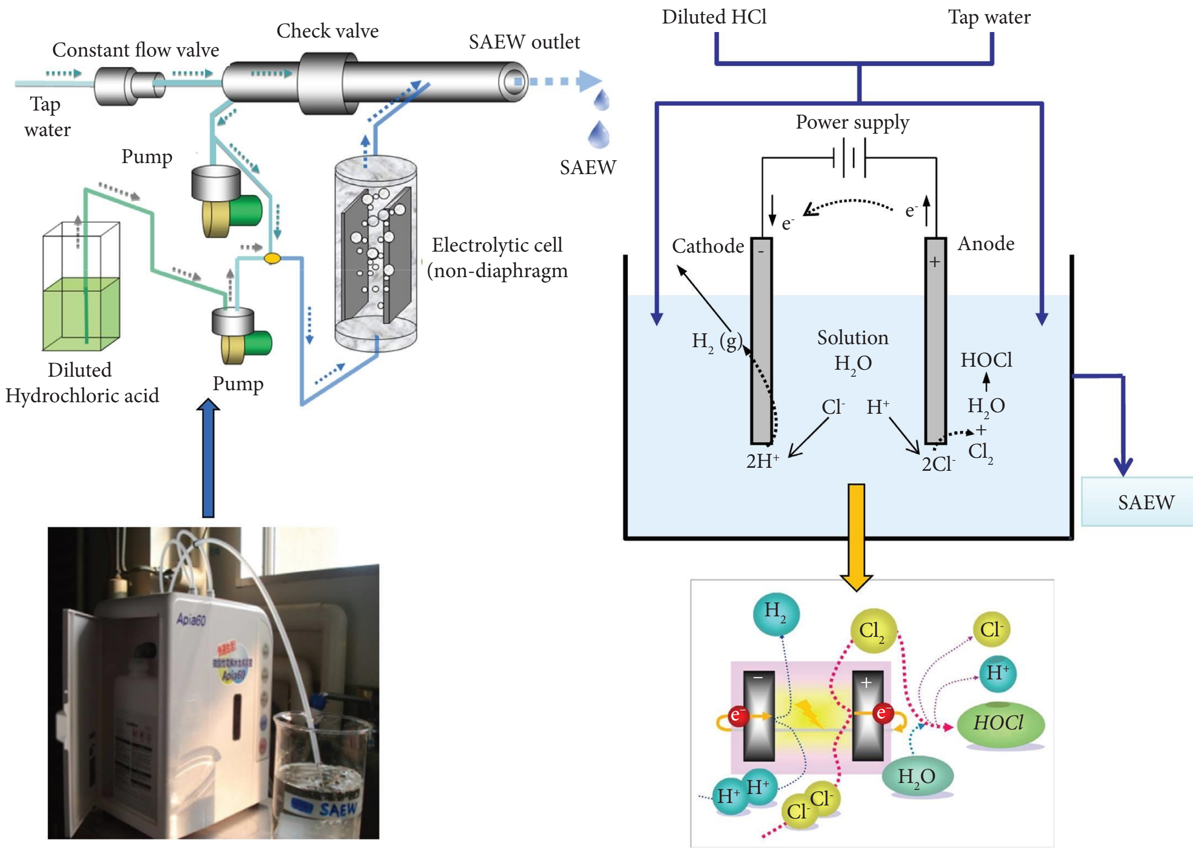

FIGURE 1: Schematic mechanism illustration of SAEW generation system and produced compounds.

TABLE 1: Common SAEW generators and their respective available chlorine concentration (ACC: mg/L).

SAEW model	Country of origin	ACC (mg/L)	References
Apia60	Japan	10–30	[46]
Apia210	Japan	10–30	Unpublished
AQUACIDO NDX-250KMS	Japan	60	[42]
Apia5000H	Japan	10–30	Unpublished
Water God HD-240L	China	10–40	[47]
Anywhere-320W	China	30–35	[41, 48]
ORPWG	China	30	[49]
Purester MP-600T	Japan	20–25	[50]
Purester MP-240	Japan	10–30	Unpublished
Purester MP-2000T	Japan	10–30	Unpublished
Apia1000H	Japan	10–30	Unpublished
HOCL series (e.g 2.5t/5t)	Japan	10–30	Unpublished
ecoTree	Korea	10–30	[43]
BD-600L	China	30–80	[36]

side effects, while maximizing the efficacy of hypochlorous acid species [16]. In recent years, SAEW has drawn attention from scientists and processing companies due to its nearly neutral pH (5.0–6.5) and lower ACC (10–30 mg/L), and its strong sanitization efficacy on food materials and food-contact surfaces has been widely acknowledged [12, 42].

Sanitizing efficacy of EW is directly affected by its fundamental properties, such as ACC (Cl_2, OCl−, and HOCl), pH, and ORP. In addition, several electrolytic parameters, including electrolyte composition, flow rate, current, salt concentration, electrode materials, water temperature, water hardness, and storage conditions, have been revealed to directly influence the properties of EW [32].

Pangloli and Hung [74] found that water hardness had a positive correlation with the levels of ACC and ORP and a negative correlation with the pH of EW. Similarly, it has been documented that the physical characteristics of SAEW and its ability to deactivate pathogens are influenced by various conditions, including water hardness. Forghani et al. [75] evaluated the effect of water hardness on the properties

Table 2: Important features of slightly acidic electrolyzed water.

Properties (features) of SAEW	Details	References
The active ingredient for sanitization	Hypochlorous acid (HOCl), >95% of ACC is in this form	[16, 55, 56]
Acidity	Slightly acidic, it has a near-neutral pH of 5–6.5	[16, 55, 56]
Available chlorine concentration (ACC)	10–30 mg/l	[16, 55, 56]
Oxidation-reduction potential (ORP)	800–900 mV	[16, 55, 56]
Microbial inactivation power	80 to 150 times than that of hypochlorite ion (OCl^-)	[3, 57, 58]
Safety	Designated as a food additive by the Japanese Government and does not produce chlorine gas when applied in food sanitization	[59]
Effects on sensory quality of foods	Does not alter the flavor, hue, aroma, or nutritional content of food	[36, 45, 60]
Antimicrobial effect	Effective against bacteria, fungi, yeast, virus, bacteria spores	[42, 57, 60–62]
Effect on environment	Can be used the same as tap water and disposed of as it is immediately after use and it is environmentally friendly as it does not produce trihalomethanes (THMs)	[63, 64]
Sterilization effect	Possesses a strong effect on bacteria, fungi, yeast and molds, virus, bacterial spores, etc.	[3, 7, 57, 58, 65]
Quick effect	Can sterilize most bacteria in the first few seconds of treatment	[43, 66–68]
Rinsing not required	Can be used in the same way as tap water and be disposed of as is after use	[69, 70]
Inexpensive	Can run at a cost only a little higher than tap water after the purchase of the generator	[5, 71]
Application	Multiple uses in every field, food and agricultural industry, medical, household sanitary, dental	
Stability on storage	Exhibits greater stability under storage conditions and poses less risks to worker health	[57]

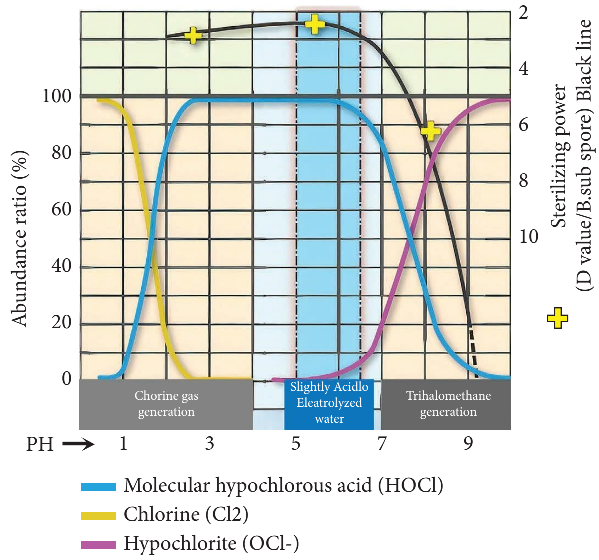

Figure 2: Available chlorine concentration as hypochlorous acid (HOCl), hypochlorite ion (OCl^-), and chlorine gas (Cl_2), as a function of pH change. The figure indicates the contained material ratio of chlorine-based sanitizer (chlorine gas, sodium hypochlorite, and chloride of lime) during the pH (acid-alkali index) change.

of SAEW, and it was observed that an increase in water hardness was accompanied by a drop in pH. While water hardness was shown to increase ACC and ORP levels, it decreased the pH of EW. Moreover, the rise in ACC (mg/L) can be attributed to an increase in the concentration of electrolytes and conductivity, both of which were induced by the existence of water hardness [74]. The typical use of SAEW is the inactivation of bacteria in food matrices that contain organic components. Organic compounds may undergo a chemical reaction with chlorine present in SAEW, resulting in the formation of combined chlorine. Hence, SAEW's anticipated antibacterial activity in organic material-containing environments is not directly proportional to the available chlorine concentration, which comprises both free and mixed chlorine [52]. The significance of water hardness as a raw material becomes even more crucial for the manufacturing of SAEW due to the strict requirements such as pH (5.0–6.5) [7]. In addition, the storage of SAEW can potentially impact the physicochemical properties and bactericidal efficacy of SAEW [76].

Forghani et al. [75] and Pangloli and Hung [74] observed that EW's fundamental properties are affected by water hardness and temperature. After its production, heating EW to 40°C could reduce its inactivation efficacy since some free chlorine is lost during heating [75].

The basic properties of EW are furthermore impacted by the type and flow rate of electrolyte, along with the electrode settings and materials [32]. Hsu [77] revealed a direct relationship between the ACC and the concentration of the electrolyte. Augmenting the concentration of electrolytes can elevate conductivity, potentially increasing chlorine production and bolstering its bactericidal efficacy. Furthermore, Forghani et al. [75] revealed that the increase in pH was triggered by the increase of electrolyte concentration. According to Martínez-Huitle and Brillas [78], the production of oxidants and other species is mostly influenced by the choice of electrode material, rather than factors such as current, temperature, and type of electrolysis. Typically, platinum serves as the anode in the EW generator. Rahman et al. [3] ordered several electrode materials to assess their effectiveness in producing free chlorine. The order of electrocatalytic activity, from highest to lowest, is Ti/IrO2, Ti/RuO2, Ti/Pt-IrO2, BDD, and Pt. Furthermore, it has been found that altering the size or gap of the electrode has a notable impact on chlorine production and electric current, while not influencing its electric efficiency and current efficiency [77]. In addition to the basic properties of SAEW, such as ACC (Cl_2, OCl^-, and HOCl), pH, and ORP, which impact its disinfecting effectiveness, several electrolytic factors, such as flow rate, salt concentration, current, electrolyte, water temperature, electrode materials, hardness, and storage conditions, must be considered and monitored during the production and use of SAEW [77]. Therefore, it is crucial to take into account and closely observe various electrolytic parameters, including current, flow rate, salt concentration, electrolyte, electrode materials, water temperature, hardness, and storage environments, in addition to the basic properties of SAEW. These parameters possess a significant impact on the sanitizing effectiveness of SAEW.

5. Microbial Inactivation Mechanisms of Slightly Acidic Electrolyzed Water

Similar to strong acidic acid electrolyzed water type, SAEW has been reported to possess a strong antimicrobial activity against different food pathogens, yeast and molds, and virus. However, action mechanisms of slightly electrolyzed water are not consensus, but a lot of theories exist. Several mechanisms are interconnected, and the effect was based on one or more ways evolving chlorine species, ORP, and others. These mechanisms specifically target bacterial enzymes, causing membrane damage and other effects [72]. Slightly acidic electrolyzed water has a pH value of 5.0–6.5 and contains a high concentration of HOCl and high ORP values. The antibacterial action of SAEW is primarily attributed to the presence of HOCl and high ORP, which has been thoroughly investigated and demonstrated to be highly effective [31, 57, 79]. In their previous study, Al-Haq et al. [1] asserted that the main factors contributing to the bactericidal activity of SAEW are a high concentration of HOCl, a high ORP, a significant amount of free available chlorine, and the presence of hypochlorite ions (OCl^-). At a pH range of 5.5–6.5, the majority of available chlorine exists as HOCl (~97%), is the primary active form of chlorine compounds, and is believed to be responsible for killing microorganisms [56]. The bactericidal efficacy of chlorine-related compounds is more pronounced in the form of nondissociated HOCl compared to dissociated OCl^-. Studies have demonstrated that HOCl is 80–150 times more efficient than an equivalent concentration of OCl^- as a sanitizing agent [3, 57, 58]. According to Schaik [80], electrochemically activated HOCl in SAEW is more effective than chemically produced HOCl in bleach by more than 400%. It is generally believed and acknowledged that the bactericidal effect of SAEW at a pH close to neutral is caused by the combination of high ORP reactions with hydrochloric acid (HOCl).

Initially, the bacteria' defensive mechanism is rendered inactive by ORP reactions that occur at the cell membrane, which damage both the outer and inner membranes. According to Fabrizio and Cutter [81], one way that ORP can kill microbes is by making their cell membranes more permeable, which allows antimicrobial agents to disrupt their metabolism and ultimately render them inactive. The study conducted by Liao et al. [82] provided additional evidence that the high oxidation-reduction potential (ORP) of SAEW can harm cell membranes, oxidize sulfhydryl compounds on cell surfaces, and disturb cell metabolic processes. Consequently, this leads to the inactivation of bacterial cells. Nan et al. [79] hold a similar argument that SAEW with high ORP effectively damaged, destroyed, or caused deformation of the outer membrane of foodborne pathogenic bacteria, such as *S. aureus* and *E. coli O157:H7*, inactivation of these pathogens being as a result of its high ORP (mV). In the same vein, the research conducted by Ding et al. [49] revealed that the disinfection mechanism of SAEW involved the disruption of the cell membrane's permeability and the cytoplasmic ultrastructures in *S. aureus* cells. The SAEW solution has an oxidation-reduction potential (ORP) ranging from 800 to 900 mV, as previously stated. This ORP has a direct and irreversible detrimental effect on the microbial cell wall. Furthermore, the configuration of water molecules undergoes electrochemical modifications, enhancing the capacity of microbicidal ions to penetrate and interact. This property is absent in traditional disinfectants [80].

The second active species of SAEW, HOCl, has indirect antimicrobial effects due to the generation of the radical OH- after HOCl permeates bacterial cells [83]. The bactericidal effect of HOCl is ascribed to its ability to infiltrate microbial cells by traversing the cell walls and membranes, as depicted in Figure 3 of the model proposed by Fukuzaki [84]. This model illustrates that the bactericidal action of EW is determined by the capacity of HOCl and −OCl to penetrate the microbial cell membrane. The presence of the lipid bilayer, a hydrophobic layer in the microbial cell membrane, prevents the penetration of ionized −OCl. At times, certain components of the microbial cell wall provide protection against the penetration of −OCl. The ionized form of hypochlorite (-OCl) is unable to pass through the microbial membrane and has demonstrated little effectiveness in killing bacteria. -OCl specifically targets the external membrane of the cell (circle A). The active agent responsible for the bactericidal effect is therefore HOCl, since it is electrically neutral and capable of permeating the cell membrane. HOCl has the ability to target both the outside membrane (circle A′) and the interior of the cell (circles B and C) [84].

After cell membrane disruption by ORP activity, HOCl can then penetrate slime layers, cell walls, and protective layers of microorganisms and oxidize it leading to the death of microorganisms [80]. In their study, Ding et al. [49] discovered that SAEW led to a decrease in TCC-dehydrogenase activity in *S. aureus*. This drop was attributed to the reaction between the HOCl present in SAEW and the enzymes, resulting in the formation of N–Cl linkages. In addition, the researchers noted the presence of protein leakage and the degradation of the bacterial ultrastructure in *S. aureus* following treatment with SAEW.

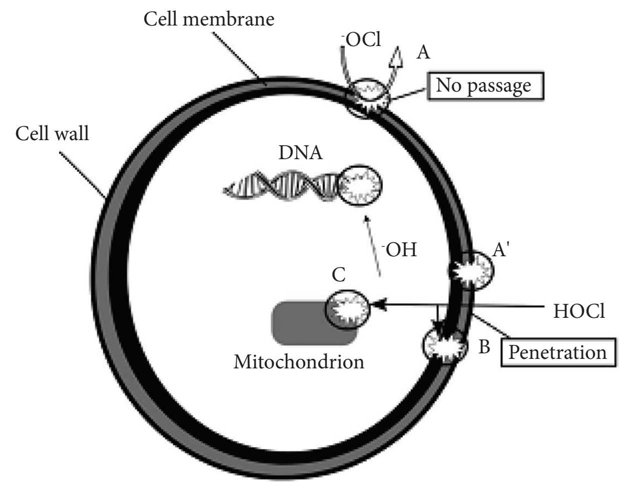

Figure 3: Model representing the germicidal activity of SAEW [84].

Assessing the bactericidal mechanism of SAEW on *E. coli*, Suzuki et al. [85] suggested that SAEW killed *E. coli* by first changing the porin-proteins and channels-proteins of the outer and inner membrane, causing them to open and remain open. Then, ATP immediately is ejected into the *E. coli* suspension by the inner pressure. HOCl then enters the *E. coli* cell through the channel holes as a result of the molecular concentration gradient. HOCl neutralizes the ATP-ase and other enzymes, destroying *E. coli*. Previous studies suggested that HOCl (undissociated) produces hydroxyl radicals after penetrating cell membranes, which in turn exert their antimicrobial activity through the oxidation of key metabolic systems [83, 84, 86]. According to Hati et al. [87], HOCl in SAEW is demonstrated to kill microbes by blocking the sulfhydryl groups of enzymes involved in carbohydrate metabolism that oxidize glucose. Kurahashi et al. [4] established that HOCl in SAEW is an essential sterilizing component in slightly acidic electrolyzed water, in contrast to hypochlorous acid solutions produced by mixing acids with sodium hypochlorite.

The third antimicrobial agent of SAEW is its available chlorine concentration in mg/L (ACC). Some studies on the antimicrobial mechanism of SAEW attribute ACC as a main factor affecting the disinfection efficacy of SAEW [16, 55, 56]. According to Li et al. [53], SAEW with an available chlorine concentration (ACC) above 12 mg/L was able to kill all *L. monocytogenes* strains in just 30 seconds, demonstrating that ACC is the main factor affecting SAEW's disinfection efficacy. As a result of its high ORP value, SAEW could disrupt or break the intracellular reactive oxygen species (ROS) balance of *L. monocytogenes* by inhibiting the antioxidant enzyme activity, thus promoting the death of

L. monocytogenes [36, 53]. In a study by Liu et al. [88], it was observed that the intracellular ROS generated by SAEW was strengthened significantly with the increase of ACC, and the cells were injured to death accordingly.

The disinfection efficacy of SAEW on spores depended primarily on ACC and treatment duration, according to Zhang et al. [65], who explored the inactivation mechanism of slightly acidic electrolyzed water on *Bacillus*. This finding is in line with a prior study [89]. Evidently, the bactericidal effect of SAEW at a pH close to neutral against various bacterial strains is caused by the synergistic effect of high ORP reactions and high hypochlorous acid (HOCl). When ORPs are activated, membranes burst, hydrochloric acid (HOCl) goes through microbial cell walls, and protective layers of microorganisms to oxidize it, leading to the death of microorganisms.

6. Advantages of SAEW over Other Food Antimicrobial Sanitizers

Slightly acidic electrolyzed water, a novel disinfectant with a strong and broad-spectrum action, is colorless, odorless, and nontoxic to both humans and the environment. It is presently applied directly to food surfaces in Japan, China, Korea, and America [69]. SAEW demonstrates potent bactericidal action within a narrow pH range of 5–6.5 in a high concentration of HOCl (roughly 95%) and a low concentration of available chlorine (10–30 mg/L) [7, 10, 12]. Similarly, a previous study has demonstrated that SAEW, at this low ACC (10–30 mg/L), exhibits comparable or greater bactericidal effectiveness than NaOCl solution (100–200 mg/L) [57, 90, 91]. This could allow the food industry to reduce the amount of chlorine used and would help to improve the safety of both products and workers. In another study, SAEW has proven to demonstrate a higher antibacterial efficacy in comparison to sodium hypochlorite water disinfection [92]. Furthermore, studies have demonstrated that SAEW exhibits an equivalent or superior capacity to inactivate all types of aerobic bacteria, molds, and yeast in freshly cut cabbage when compared to the use of sodium hypochlorite disinfectant treatment [60].

Due to its neutral pH and low chlorine concentration, studies by Abadias et al. [15], Possas et al. [67], Yan et al. [93], and Zhao et al. [94] have shown that SAEW has a lower effect on the corrosion of processing equipment and is less likely to cause irritation to the hands compared to StAEW. Furthermore, studies have demonstrated that SAEW exhibits less phytotoxicity in plants and presents fewer safety risks associated with the release of Cl_2 gas [16]. SAEW, which has a pH range of 2.0 to 3.0, is a cost-effective and safe approach for preserving fresh produces after harvest, as demonstrated by Song et al. [5] and Sun et al. [71]. Compared with StAEW ($2.0 \leq pH \leq 3.0$), SAEW is a low-cost and safe postharvest approach for fresh produces [5, 71]. SAEW has greater advantages and fewer drawbacks than StAEW, mostly due to its pH level and the kind of chlorine it contains. These factors contribute to its enhanced efficacy and reduced corrosiveness. Operators and employees are at a reduced risk as it does not produce chlorine gas and may be transformed into ordinary water after use, without emitting hazardous gasses [95].

The advantage of the use of electrolyzed water at neutral pH in comparison with strong acidic pH is that it does not affect the pH, surface color, or general appearance of fresh-cut vegetables [14]. With SAEW, there is no residue of sodium chloride after packaging and no denaturing of the products due to sodium chloride. It is nearly odorless, and no smell remains behind after application on food and agricultural products. SAEW can be used the same as tap water and disposed of as it is immediately after use, and it is environmentally friendly as it does not produce trihalomethanes (THMs) [64].

Recently, SAEW has been found to have greater stability during storage due to a considerable reduction in chlorine loss at pH levels between 5 and 6.5. Consequently, the factor responsible for the bactericidal effect of SAEW is more stable than the similar factor in StAEW [11, 57, 96]. A previous study has additionally shown that SAEW can preserve the factors that contribute to its ability to kill bacteria, such as ACC, pH, and ORP, for an extended period of time when stored in tightly sealed containers [12]. This characteristic makes it particularly suitable for use in situations where on-site production and application are not feasible, such as in rural areas of developing countries with unreliable power supply. SAEW is extensively advocated in the field of food preservation due to its exceptional antibacterial properties, cost-effectiveness, ease of application, and environmentally benign nature [13, 18, 97]. With these, SAEW is particularly attractive for practical applications in the food industry elsewhere.

7. Application of Slightly Acidic Electrolyzed Water (SAEW) in the Food Industry

Slightly acidic electrolyzed water, a recently discovered sanitizer, has demonstrated promising and secure outcomes in several prior investigations. It is regarded as a versatile and very effective bactericide that is increasingly being used in the food industry. Studies have shown that SAEW exhibits potent antimicrobial properties against various types of bacteria, including both pathogenic and nonpathogenic bacteria, as well as spores, viruses, and fungi. These effects have been observed both *in vitro* and on different food and agricultural items [42, 57, 60, 62, 98]. SAEW's mild pH makes it more suitable for usage in the food industry [16, 55, 56]. The key feature of SAEW is its ability to inactivate microorganisms at low chlorine levels, resulting in reduced residual chlorine on vegetables following disinfection treatment, as compared to other chlorine sanitizers [99]. A previous study has shown that SAEW exhibits comparable bactericidal activity to StAEW against various bacteria and fungi found on fruits and vegetables, including *Listeria spp.* [10, 100], *Salmonella spp.* [46], *Coliform populations* [101, 102], *Bacillus spp.* [103], and *Escherichia coli* [46]. Ding et al. [104], Hao et al. [102], Issa-Zacharia et al. [46], Koide et al. [12], and Tango et al. [10] also observed that SAEW had a noteworthy antibacterial effect on a variety of fruits and sprouts, including apples, cherry tomatoes, celery, strawberries, cilantro, cabbage, and lettuce.

7.1. Inactivation of Foodborne Pathogens in Suspension (In Vitro) Using SAEW. Several studies have reported a strong bactericidal effect of SAEW on most pathogenic and nonpathogenic bacteria *in vitro* [16, 57, 61]. The antibacterial activity of SAEW against several pure cultures of foodborne pathogens that pose a significant public health issue is summarized in Table 3. After subjecting a pure culture of *Salmonella enteritidis* to a 2-minute SAEW (with a pH range of 6.3–6.5 and an ACC concentration of 2 mg/L) treatment at temperatures of 4, 20, and 45°C, the population decreased to less than 1.0 $\log_{10}$ CFU/ml [57]. When a solution containing SAEW with a chlorine concentration exceeding 4 mg/L was used at temperatures of 4, 20, and 45°C, there was an estimated decrease of 8.2 $\log_{10}$ CFU/ml. It was found that the bactericidal efficacy of SAEW was enhanced with increased chlorine availability, irrespective of temperature [57]. In another study, Guentzel et al. [16] reported a complete inactivation (>6.0 $\log_{10}$CFU/ml reduction) of pure cultures of *Escherichia coli*, *Salmonella typhimurium*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Enterococcus faecalis*. Likewise, Issa-Zacharia et al. [98] demonstrated that SAEW (pH 5.8, 21 mg/L ACC) successfully decreased the population of *Escherichia coli* and *Staphylococcus aureus* (*in vitro*) by >5 $\log_{10}$CFU/ml after only 1.5 min of exposure, while the treatment of pure culture of *Salmonella* spp. using SAEW (pH 5.6, 23 mg/L ACC) for 1 min resulted in >5 $\log_{10}$CFU/ml of their population [98]. An in vitro assessment was conducted to examine the impact of ACC and pH of SAEW on the inactivation of pathogenic microorganisms. Kim et al. [47] have provided more evidence that SAEW has the ability to completely eradicate pure cultures of *Escherichia coli, Salmonella enterica, Typhimurium, Staphylococcus aureus*, and *Bacillus cereus* spores within a treatment time of 1 minute. The study showed that when the pH value is 6.0 and the concentration of free chlorine is 20 ppm, a 1-minute treatment with SAEW is effective in killing roughly 8-9 log CFU/mL of all foodborne pathogens tested [47]. This further confirms that SAEW can effectively reduce or kill food pathogens in vitro. In the disinfection test on pure culture, exposure of SAEW (ACC 33 mg/L, pH 6.4, and ORP of 834.9 mV) significantly reduced *S. aureus* by 5.8 log CFU/mL in 1 min [49]. In a separate experiment, Li et al. [109] found that exposing *B. subtilis* and *B. cereus* spores to a 5-minute treatment of SAEW with an ACC concentration of 60 mg/L, a pH of 5.89, and an ORP of 930 mV resulted in a substantial decrease in spore levels. The reduction was around 4.94 log CFU/mL for *B. subtilis* and 6.22 log CFU/mL for *B. cereus*. In a similar vein, Kurahashi et al. [4] observed that SAEW with around 30 mg/L of available chlorine exhibited potent sterilizing action, effectively eliminating *Bacillus* spores within 15 minutes. It was found that a concentration of 30 mg/L ACC was able to destroy pure cultures of *E. coli, P. aeruginosa, S. enterica, S. aureus,* and *S. epidermidis* within 15 seconds. In addition, *C. cladosporioides* was removed within 60 seconds of exposure to the same concentration of SAEW [4]. As recognized by many studies that SAEW has shown strong bactericidal efficacy on foodborne pathogens, therefore SAEW is a promising sanitizer in the food industry.

7.2. Inactivation of Foodborne Pathogens on Food Products (In Vivo) Using SAEW. The phytochemical components and numerous nutrients included in fruits and vegetables help to lower the chance of developing chronic diseases, making them an essential component of a healthy diet. The storage quality of fresh-cut fruits and vegetables is greatly impacted by microbes, which must be controlled. Researchers from all over the globe have explored nonthermal processing methods to reduce the amount of microbes on various foods, including meat, poultry, and aquatic products, since traditional thermal sterilization methods do not work well enough [45]. The utilization of slightly acidic electrolyzed water as a sterilization technique has attracted considerable attention owing to its exceptional efficacy in disinfection and its environmentally friendly characteristics [47, 99, 110]. SAEW has attracted significant scientific interest in recent years due to its almost neutral pH range of 5.0–6.5 and low ACC levels of 10–30 mg/L. Its powerful disinfection capabilities on food products and surfaces that come into contact with food have been acknowledged by researchers [12, 108]. Studies have now demonstrated the strong antibacterial activity of SAEW against foodborne pathogens on several foods and agricultural products as seen in Tables 4 and 5. Table 4 summarizes the antimicrobial effectiveness of SAEW on different fresh fruits and vegetables, while its effectiveness on fresh red meat, poultry, and aquatic products is shown in Table 5. Research undertaken by Ding et al. [104], Mansur et al. [117], and Zhang et al. [7] has shown that SAEW treatment is highly successful in reducing the presence of mold, bacteria, and viruses in fresh produces, which are potential causes of food poisoning. The application of a 10-minute SAEW treatment resulted in a reduction of aerobic bacteria by 3.29 and 3.59 $\log_{10}$CFU/g in cherry tomatoes and strawberries, respectively. In addition, there was a decrease of 2.32 and 3.01 log in yeast and mold, respectively [104]. Suzuki [121] investigated the effectiveness of SAEW on both whole and cut carrots, Japanese radishes, onion, sweet potatoes, burdock, lettuce, cucumber, strawberries, tomatoes, and eggplant. Washing with SAEW effectively reduced total aerobic bacteria from tested produces by 1 to 2 $\log_{10}$CFU/g with the skin not removed, while the similar test resulted in 3.0 to 4.5 $\log_{10}$CFU/g when the skin was removed before washing treatment [122]. Other studies reported a more than 2 $\log_{10}$CFU/g of total aerobic bacteria from spinach leaves [123] and 1.3 to 1.6 $\log_{10}$CFU/g reduction of *E. coli* inoculated on Japanese mustard green (*mizuna*) as a result of a 5-minute dip-treatment using SAEW [90]. A similar effect was reported by Koide et al. [12] in which washing fresh-cut cabbage with SAEW reduced total aerobic bacteria by about 1.5 $\log_{10}$CFU/g, while the yeast and mold count was reduced by 1.3 $\log_{10}$CFU/g. Cao et al. [57] investigated the effectiveness of SAEW in treating shell eggs. The SAEW method effectively eliminated *S. enteritidis*, pathogenic bacteria, from deliberately contaminated shell eggs. The eggs were subjected to SAEW treatment for a duration of 3 minutes, resulting in a reduction of 6.5 $\log_{10}$CFU/g. The data suggest that SAEW has potential as a substitute disinfectant for reducing or eradicating bacteria on shell eggs. The inactivation efficacy of slightly acidic electrolyzed pathogens

Table 3: Antimicrobial activity of slightly acidic electrolyzed water against microorganisms in suspension (*in vitro*).

Foodborne pathogen	Time (min)	pH	Physicochemical properties of SAEW			References
			ORP (mV)	ACC (mg/L)	Log red. (CFU/ml)	
B. subtilis and *B. cereus spores*	5	5.89	930	60	>5.0	[105]
Salmonella enteritidis	2	6.3	850–900	15	>5.0	[57]
Escherichia coli, Staphylococcus aureus, Salmonella typhimurium, Listeria monocytogenes, Escherichia faecalis	≥5	6.5	800	20	>6.0	[16]
P. aeruginosa, S. enterica, S. aureus, and *E. coli (O157:H7)*	0.25	5.9	800	30	>5.0	[4]
Staphylococcus aureus, Escherichia coli 0157:H7, Listeria monocytogenes	≥5	6.3	500	5	>5.0	[106]
C. cladosporioides	1	5.9	800	30	>5.0	[4]
S. enteritidis, E.coli O157:H7, and *S.aureus*	≥5	5.74	902	60	>3.0	[91]
Escherichia coli and *Staphylococcus aureus*	1.5	5.8	948	21	>5.0	[98]
Pseudomonas deceptionensis	1	5.9	945	64	>5.0	[107]
Escherichia coli, Staphylococcus aureus, and *Salmonella* spp.	1	5.6	940	23	>5.0	[98]
Escherichia coli	≥5	6.5	850	20	>6.0	[16]
Listeria monocytogenes	≥5	6.5	850	20	>6.0	[16]
Salmonella typhimurium	≥5	6.5	850	20	>6.0	[16]
Staphylococcus aureus	1	6.4	835	33	>5.0	[49]
Escherichia coli, Salmonella enterica, Salmonella typhimurium, Staphylococcus aureus, and Bacillus cereus spores	1	6	850	20	>8.0	[47]
Listeria monocytogenes	≥5	6.5	850	20	>5.0	[76, 108]
B. cereus (spores), B. subtilis (spores)	15	5.9	800	30	>5.0	[4]

present in spinach leaves was also investigated by Rahman et al. [111] in which SAEW treatment effectively reduced total aerobic bacteria count, yeast and molds, *E. coli*, and *L. monocytogenes* from spinach by 1.93, 1.64, 2.4, and 2.6 $\log_{10}$CFU/g, respectively. Another similar study reported that a 5-minute treatment of lettuce using slightly acidic hypochlorous water (SAEW; pH 5–6.5, 30 mg/L ACC) effectively decreased the total aerobic bacteria by 2 $\log_{10}$CFU/g [112]. In addition, in mung bean seeds and sprouts, SAEW (ACCs of 20 and 80 mg/L) treatment decreased *E. coli* and *S. enteritidis* by 1.27–1.76 and 3.32–4.24 $\log_{10}$CFU/g and 3.12–4.19 $\log_{10}$CFU/g, respectively [124]. In a recent study by Song et al. [5], an experimental verification was conducted on fresh cabbage to test the effectiveness of the optimized SAEW treatment. A reduction of 5.94 ± 0.07 $\log_{10}$CFU/g of *Pectobacterium carotovorum* subsp. *Carotovorum* was observed following this treatment.

The effectiveness of SAEW on fresh red meat, poultry, and aquatic products is shown in Table 5. SAEW has been proposed as a potential sanitizer to be used for sanitization of egg shells as an environmentally friendly disinfection agent [57, 91]. After a 3-minute SAEW treatment, the number of *S. enteritidis* CFU/g on shell eggs was reported to decrease by 6.5 $\log_{10}$CFU/g, and no *S. enteritidis* survival was detected in the waste wash SAEW [57]. Rahman et al. [31] conducted a study to assess the effectiveness of SAEW in reducing *L. monocytogenes* and *S. typhimurium* on fresh chicken breast flesh. According to this study, when exposed to a 10-minute treatment of SAEW with 10 ppm of active chlorine at a temperature of 23°C, there was a decrease of 2.32 $\log_{10}$CFU/g for *L. monocytogenes* and a decrease of 1.9 $\log_{10}$CFU/g for *S. typhimurium*.

In other study by Tango et al. [118], the SAEW treatment (pH 6.3, ORP 820–934 mV, and ACC 25 mg/L) demonstrated a substantial sanitization effect against *S. aureus*, *L. monocytogenes,* and *E. coli O157:H7* on fresh beef. In addition, a decrease in bacterial counts by 0.63–2.52 $\log_{10}$CFU/g with increases in the contact time was reported [118]. Few studies have been carried out on the use of SAEW to control bacteria in pork. A variety of bacteria found in pork products have the potential to spread foodborne illnesses, which in turn can harm both people's health and the economy. According to Rahman et al. [115], fresh pork treated with SAEW or AEW demonstrated improved microbiological stability, longer shelf life at different temperatures, and minimal impact on sensory quality. Fresh pork treated with SAEW (pH 6.8, ORP 700–720 mV, and ACC 10 mg/L) was found to inactivate *E. coli O157:H7* and *L. monocytogenes* just as well as with AEW. In addition, Mansur et al. [117] have demonstrated the efficacy of SAEW against *E. coli, L. monocytogenes, Salmonella typhimurium,* and *S. aureus,* which are commonly found in pork products. According to the current research on food safety, it can be concluded that although the use of SAEW reduced bacterial levels in fish and animal-based foods to some extent, it is important to prioritize strict manufacturing and slaughter hygiene practices as vital elements of a comprehensive food safety system to guarantee the production of safe products [125]. SAEW has therefore emerged as a promising and new approach, especially in agricultural contexts, for the purpose of sterilizing fresh-cut fruit, vegetables, meat, poultry, and aquatic items.

8. Effect of Slightly Acidic Electrolyzed Water on Postharvest Quality Control of Fruits and Vegetables

Fruits and vegetables recently harvested are very perishable and susceptible to deterioration throughout the process of production, transportation, and storage. Microbes are the primary determinant of the storage quality of fresh-cut fruit and vegetables. Microbial infection, physiological aging, nutritional loss, tissue discoloration, texture softening or lignification, and flavor deterioration can all be linked to the mechanical damage caused to cells and tissues during peeling and cutting procedures. These factors detrimentally affect the storage quality and diminish the longevity of the product [126].

Up to now, research on the application of SAEW in the field of fresh-cut and vegetables has mainly focused on the bactericidal effects on surface microbes, but there are relatively few reporting the effects of SAEW on the postharvest physiology, quality, and storage properties of fruits and vegetables on storage. Despite their limited number, their research has shown promise in the use of SAEW in improving the quality of fruits and vegetables.

It has been reported that SAEW treatment on fresh-cut fruits and vegetables shows a positive impact on micronutrients, sugar content, color, and other sensory quality parameters. The study conducted by Gao et al. [45] demonstrated that in comparison with the control group, SAEW treatment resulted in much higher total sugar content in the treated fresh-cut apples. In addition, treatment of fresh-cut apples with SAEW prevented them from changing in color, which in turn slowed down their browning and exerted a certain protective effect on the color [45]. A key indication of the quality change that occurs in fresh-cut apples when they are stored is their total sugar level, which affects the color, aroma, taste, texture, and nutritional value of these fruit items. A recent study by Gao et al. [45] revealed that SAEW treatment not only exhibited a satisfactory bactericidal effect on the surface microbes of fresh-cut apples but also did not adversely affect the apples' sensory qualities. In addition, SAEW treatment on fresh-cut apples mitigated the degradation of vitamin C, decreased weight loss and browning processes, and preserved the pH levels of the tissues. Consequently, this treatment effectively retards the deterioration of crucial quality parameters during storage, thereby extending the shelf life of fresh-cut apples [45]. In their study, Ling et al. [127] found that weakly acidic electrolyzed water effectively decreases the activity of *polyphenol oxidase*, hence preventing the browning process in *Zizania latifolia*. The observed less color alteration in fruit treated with SAEW, as compared to fruit treated with sterile water, may be attributed to the antioxidant properties of vitamin C, as noted by Gao et al. [45]. In a similar investigation, the application of SAEW (with a pH value of 6.0,

Table 4: Antimicrobial activity of slightly acidic electrolyzed water on different fruits and vegetables (*in vivo* application).

Food product	Indicator bacteria	log red[†CFU/g]	Effectiveness	References
Spinach	*Escherichia coli O157:H7*	2.40	+++	[111]
Spinach	*Listeria monocytogenes*	2.80	+++	[111]
Spinach	*Yeast and molds*	1.64	++	[111]
Spinach	Aerobic bacteria counts	1.93	++	[111]
Cut cabbage	Aerobic bacteria counts	1.50	++	[12]
Cut cabbage	Yeast and molds	1.30	++	[12]
Lettuce	*Viable bacteria count*	2.00	++	[112]
Lettuce	*Enterococcus faecalis*	2.80	+++	[16]
Spinach	*Escherichia coli O157:H7*	2.49	+++	[111]
Sliced carrot	Aerobic bacteria counts	2.20	+++	[60]
Sliced carrot	Yeast and molds	1.90	++	[60]
Chinese cabbage	*E. coli/L. monocytogenes*	1.22/1.19	++	[38]
Lettuce	*E. coli/L. monocytogenes*	1.23/1.20	++	[38]
Sesame leaf	*E. coli/L. monocytogenes*	1.15/1.31	++	[38]
Spinach	*E. coli/L. monocytogenes*	1.12/1.48	++	[38]
Cabbage	*Pectobacterium carotovorum subsp. carotovorum*	5.94	++++	[5]
Cherry tomato	*Total bacteria*	3.29	+++	[104]
Cherry tomato	*Yeast and molds*	3.59	+++	[104]
Strawberry	*Total bacteria*	2.32	+++	[104]
Strawberry	*Yeast and molds*	3.01	+++	[104]
Celery	*Total aerobic bacteria*	4.33	++++	[105]
Celery	*Yeast and molds*	3.86	+++	[113]
Celery	*Escherichia coli*	2.74	+++	[46]
Celery	*Salmonella* spp.	2.87	+++	[46]
Cilantro	*Total aerobic bacteria*	4.14	++++	[105]
Cilantro	*Yeast and molds*	3.75	+++	[105]
Lettuce	*Escherichia coli*	2.84	+++	[46]
Lettuce	*Total viable count*	1.9	++	[76]
Lettuce	*Salmonella* spp.	2.91	+++	[46]
Lettuce	*Total microbial count*	1.9	++	[114]
Cabbage	*Total microbial count*	1.5	++	[12]
Cabbage	*Yeast and molds*	1.3	++	[12]
Cilantro	*Escherichia coli O78*	2.49	+++	[103]
Cilantro	*Bacillus subtilis I.1849*	1.54	++	[103]
Shell eggs	*Salmonella enteritidis*	6.5	++++	[57]
Spinach	*Salmonella typhimurium*	2.14	+++	[16]
Spinach	*Listeria monocytogenes*	2.94	+++	[16]
Spinach	*Enterococcus faecalis*	2.86	+++	[16]

++++, bacterial reduction being more than 4 log CFU/g; +++, bacterial reduction being between 2 and 4 CFU/g; ++, bacterial reduction being between 1 and 2 CFU/g; +, bacterial reduction being less than 1 log CFU/g.

ORP of 1340 mV, and ACC of 80 mg/L) to carambola fruit was found to effectively decrease the rate of respiration, hinder the increase in cell membrane permeability, and delay visible color alteration [36]. This suggests that treating fruits with SAEW can improve postharvest quality of fruits. Zhang et al. [36] further observed that SAEW treatment of carambola fruit resulted in higher levels of bioactive compounds and nutritional components, including polyphenols, reducing sugars, flavonoids, total soluble sugar, sucrose, vitamin C, and total soluble solid (TSS). In addition, the treated fruit exhibited increased titratable acidity (TA). Based on these findings, Zhang et al. concluded that SAEW treatment enhances the quality of carambola fruit [36]. These findings align with earlier research that have shown that SAEW treatment can enhance the nutritional markers of pea sprouts, including vitamin C, total protein, and soluble sugar [70]. According to a recent study by Zhao et al. [128], SAEW treatment improved nutritional indices of fresh-cut kiwifruit by lowering TA levels and suppressing the starch-to-sugar conversion. In addition, SAEW can increase the amounts of total phenols and flavonoids in fresh-cut kiwifruit, which boosts its antioxidant capacity [94]. Furthermore, according to Lin et al. [129], SAEW treatment can delay the decrease in in total phenolic content in eggplant.

Furthermore, Li et al. [130] found that SAEW treatment of broccoli sprouts increased their antioxidant capacity and nutritional profile by accumulating the essential amino acid proline, phenolic acids, and flavonoids, among other things. In addition, treatment with SAEW (ACC 50 mg/L) resulted in the highest total phenolic acid concentration in broccoli sprouts and enhanced their concentration of phenolic acids [130]. Furthermore, Zhang et al. [36] claimed that carambola treated with SAEW demonstrated an elevated level of commercial acceptability and firmness, while experiencing reduced weight loss and peel browning index compared to the untreated fruits. In light of these findings, it was

Table 5: Antimicrobial activity of slightly acidic electrolyzed water on meat, poultry, and aquatic products (*in vivo* application).

Food product	Indicator bacteria	Log red$^{†CFU/g}$	Effectiveness	Reference
Fresh pork	*Listeria monocytogenes*	1.8	++	[115]
Fresh pork	*Listeria monocytogenes*	1.7	++	[116]
Fresh pork	*Escherichia coli*	1.7	++	[115]
Fresh pork	*Escherichia coli*	1.2–1.6	++	[117]
Fresh pork	*Listeria monocytogenes*	1.7	++	[115]
Fresh pork	*Salmonella typhimurium*	1.2–1.6	++	[117]
Fresh pork	*Staphylococcus aureus*	1.2–1.6	++	[117]
Chicken carcass	*Listeria monocytogenes*	2.3	+++	[31]
Chicken carcass	*Staphylococcus aureus*	1.9	++	[31]
Chicken carcass	Total viable count	1.5	++	[31]
Shell eggs	Coliforms	1.4	++	[91]
Shell eggs	*Escherichia coli O157H7*	2.7	+++	[91]
Shell eggs	*Staphylococcus aureus*	2.8	+++	[91]
Fresh beef	*Escherichia coli*	1.1–2.1	++	[118]
Fresh beef	*Listeria monocytogenes*	1.1–2.2	++	[118]
Fresh beef	*Salmonella typhimurium*	0.7–1.8	+++	[118]
Fresh beef	*Staphylococcus aureus*	0.8–1.6	+++	[118]
Fresh beef	*Total viable count*	1.9–2.7		[118]
Shrimp	*Vibrio parahaemolyticus*	4.41	++++	[119]
Crab	*Vibrio parahaemolyticus*	4.06	++++	[119]
Shellfish	*Escherichia coli*	3.1	+++	[120]
Shellfish	*Listeria monocytogenes*	3.1	+++	[120]
Shellfish	*Vibrio parahaemolyticus*	3.1	+++	[120]

++++, bacterial reduction being more than 4 log CFU/g; +++, bacterial reduction being between 2 and 4 CFU/g; ++, bacterial reduction being between 1 and 2 CFU/g; +, bacterial reduction being less than 1 log CFU/g.

proposed that the application of SAEW treatment resulted in superior fruit quality and nutritional content, which could potentially enhance the storage properties of harvested carambola. According to Zhang et al. [36], it was speculated that SAEW treatment might possibly induce the production of flavonoids and polyphenols, which would therefore delay the senescence of carambola fruit while maintaining its quality. According to Li et al. [130], SAEW has the potential to promote the accumulation of phenolic compounds in broccoli sprouts, making it an attractive inducer for bioactive compound-focused food industries. Therefore, SAEW could be a potential and useful strategy for boosting the accumulation of bioactive compounds in plants if applied extensively [109].

9. Conclusion

The advent of novel slightly acidic electrolyzed water (SAEW) has effectively mitigated the corrosion challenges associated with StAEW and AEW. Developed by Japanese companies over two decades ago, SAEW received endorsement as a food additive by the Japanese Ministry of Health, Labor, and Welfare in 2002 and subsequent approval as a control agent in 2014 by the Ministry of Agriculture, Forestry, and Fisheries, along with the Ministry of the Environment. Its rapid integration within the realm of food sanitation for agriculture and the food industry is underpinned by its potent antimicrobial properties, stemming from a substantial hypochlorous acid concentration. Marked as an eco-friendly disinfectant, SAEW (pH 5–6.5; 10–30 mg/L ACC) emerges as a commendable solution, curbing the deleterious impact of chlorine residues on human and environmental well-being. SAEW not only excels in its preservation capabilities during storage but also exhibits minimal influence on pH, surface aesthetics, and overall appearance of fresh-cut produce. Notably divergent from StAEW, SAEW exhibits significantly reduced tendencies to corrode processing equipment, cause skin irritations, induce phytotoxicity in plants, or generate safety concerns through chlorine off-gassing. Consequently, SAEW emerges as an innovative and auspicious avenue, particularly in agricultural settings for sterilizing of fresh-cut fruit, vegetables, meat, poultry, and aquatic products. Moreover, its applicability extends to the food processing industry and household kitchens, serving as a reliable agent for disinfecting food materials and processing equipment.

Data Availability

The data that support the findings of this study can be obtained from the author on reasonable request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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