Wiley
Journal of Food Quality
Volume 2024, Article ID 3272823, 18 pages
https://doi.org/10.1155/2024/3272823

WILEY

Review Article

Electrolyzed Water: A Promising Strategy for Improving Food Quality and Safety of Fruits, Vegetables, and Meat

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Received 2 August 2024; Accepted 24 October 2024

Academic Editor: Eduardo Puértolas

The growing demand for sustainable and healthy practices has led to an increased interest in the electrolyzed water (EW) application. This technology has garnered widespread acceptance as a sanitizer within the food industry. It also enhances the nutritional, functional, and sensory properties of food products to improve quality and safety. This review undertakes a comprehensive review of the recent advancements in electrolysis technology, exploring its applications in fruits and meat industry and its impact on nutritional, functional, microbiological, safety, and sensory characteristics. It is concluded that the EW should be considered an essential component of industrial equipment sanitization and food product decontamination by offering antimicrobial benefits and promoting functional component accumulation. Nevertheless, the effectiveness of EW can be compromised by the presence of organic matter and equipment corrosion. Furthermore, it provides a concise overview of EW generation, elucidates the influential factors governing its production, and delineates prospective directions for research and development in this field.

Keywords: electrolyzed water; food industry; food processing; food safety and sanitation; green technology; sustainable food products

1. Introduction

The safety of food products is a paramount concern given their susceptibility to various forms of microbial contamination. The increasing globalization of the food trade has heightened concerns over foodborne illnesses, which affect millions of people worldwide each year [1]. As consumer demand for safe, high-quality food products rises, ensuring food safety across the supply chain has become an urgent priority. The diverse composition of meat, fish, vegetables, and fruits makes them vulnerable to microbial pathogens, posing a significant risk to public health [2]. The annual occurrence of foodborne illnesses underscores the urgent need for effective strategies to ensure food safety [3]. In addition to the profound impact on public health, microbial contamination in food also imposes substantial economic losses. Microbial spoilage stands out as one of the primary contributors to the qualitative deterioration of food products [4]. As a result, the development of effective, sustainable sanitization strategies that address both food safety and economic concerns is imperative for the global food industry. So, addressing this issue requires not only a commitment to safeguarding public health but also implementing measures that mitigate economic losses associated with contaminated food. The global food industry faces increasing pressure to adopt more sustainable and efficient sanitization methods that not only protect public health but also reduce the environmental impact of traditional chemical disinfectants.

Physical treatments, such as heat treatment, constitute the primary approach in microbial decontamination. However, heat treatments can compromise the quality of certain foods. In such instances, chemical treatments are preferred, with commonly used disinfectants including chlorine, peracetic acid, and hydrogen peroxide [5]. Recent studies have linked the use of these products to the formation of toxic chemical byproducts, such as bromide precursors, trihaloacetic acids, nitrates, and halonitriles, which pose risks to human health and the environment [6].

Utilized in Japan since the 1980s, electrolyzed water (EW) was initially developed in Russia, and electrolysis technology has been employed in medical institutions for water purification, regeneration, and disinfection. Subsequently, EW found application in the sterilization of medical instruments within hospital settings and expanded its usage to other fields, including agriculture [7]. Through technological advancements, EW has grown in popularity. In the present era, the escalating consumer demand for ecologically responsible, sustainable, and health-enhancing practices is witnessing a steady increase. In recent years, there has been a growing popularity of small kitchen appliances that produce EW, particularly in Asian countries. These devices are increasingly equipped with additional features, such as ultrasound or LED lamps emitting specific wavelengths of radiation, which enhance their antimicrobial efficacy and broaden their application in food safety [8]. The widespread adoption of such technologies underscores the relevance of researching EW for ensuring microbiological quality in food products and minimizing food waste [9]. This global trend highlights the importance of further exploring the mechanisms, benefits, and limitations of EW treatments in food systems.

In this context, EW has garnered significant recognition in the food industry as a sanitizer to decrease or remove the microbial load on end products, and surface areas of the processing unit [10]. The Health, Labor, and Welfare Ministry of Japan has permitted EW to be used as an ingredient of food [9]. Moreover, the Environmental Protection Agency (EPA) has also allowed the use of EW generators in food processing industries [11]. EW offers numerous advantages over traditional disinfection systems, including cost-effectiveness, eco-friendly, effective sanitizing agent, ease of application, onsite production, and safety for both humans and the environment [12].

This review collects recent advances in the utilization of EW in fruits, vegetables and meat, focusing on the microbiological and qualitative outcomes resulting from various treatments and types of EW.

2. Generation of the Different Types of EW

EW has garnered significant attention as a novel sanitizing technique due to its antimicrobial efficacy against a wide range of microorganisms [13]. The production of EW involves an electrolysis chamber, which may contain diluted substances such as sodium chloride (NaCl) or hydrogen chloride (HCl) [10]. During electrolysis, a dilute salt solution is subjected to an electric current, with a diaphragm separating the anode and cathode (Figure 1). The resulting EW can be classified into alkaline, acidic, or neutral types, depending on production conditions, electrolyte solution, and equipment used [10].

In addition to NaCl and HCl, other substances, such as citric acid, acetic acid, sodium bicarbonate, and sorbate, can also be used to modify the properties of EW. For example, citric acid and acetic acid can lower the pH of the solution, making it more acidic, which enhances its antimicrobial properties due to the increased production of hypochlorous acid (HOCl), a potent disinfectant [14]. Sodium bicarbonate, on the other hand, can increase the pH, resulting in alkaline EW (AlEW), which has been shown to have effective cleaning properties and the ability to degrade biofilms [15]. Sorbate can be added to enhance the antimicrobial spectrum of EW, particularly against yeasts and molds, further improving the preservation of food products [16].

These modifications also influence the oxidation–reduction potential (ORP) of the washing solution, which is a key indicator of its disinfection efficacy. Acidic EW (AcEW) typically has a high ORP (> 1000 mV), making it highly effective at inactivating microorganisms by disrupting cell membranes and oxidizing cellular components [17]. In contrast, neutral and AlEW have lower ORP values but can still exhibit strong antimicrobial activity due to the presence of reactive oxygen species [18]. The addition of substances such as citric acid or acetic acid generally increases the ORP, thereby improving the disinfection capacity of the solution.

Electrolyzed oxidizing water (EOW), which has a pH range of two to three, an ORP exceeding 1100 mV, and an available chlorine concentration (ACC) of 10–90 ppm, is produced at the anode [19]. Simultaneously, AlEW is generated at the cathode, characterized by a pH of 10–13 and an ORP between −800 and −900 mV [20].

Recent research has explored new forms of EW. Slightly acidic EW (sAEW) is produced in a single-cell chamber, with a pH between 5.5 and 6.5, an ORP between 800 and 900 mV, and an ACC of 10–80 ppm [21]. This type of EW is generated either through the electrolysis of HCl or a combination of HCl and NaCl in a single-cell unit [22]. Neutral EW (NEW) is produced by mixing hydroxide (OH^-) ions with anodic solutions [23].

EW production systems can be categorized based on the presence or absence of a diaphragm. Systems with a diaphragm produce AcEW and AlEW, while those without a diaphragm generate sAEW and NEW [9].

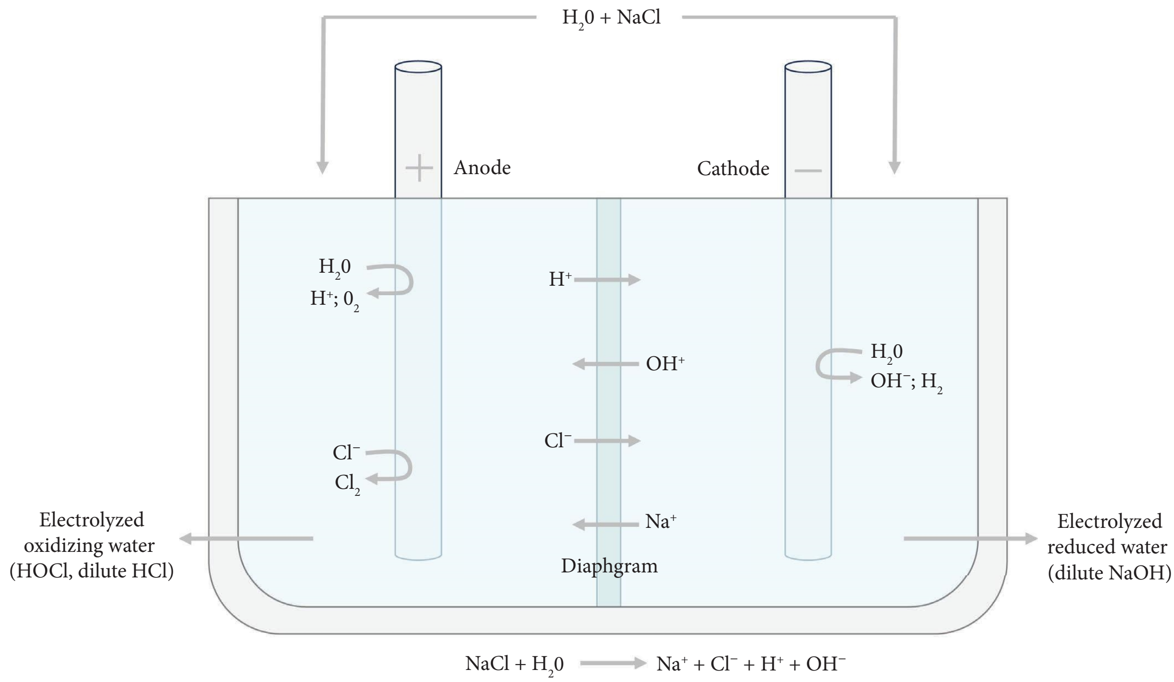

Figure 1: Generation of oxidizing and reducing electrolyzed water in an electrolytic cell. EW, electrolyzed water.

3. EW in Fruits and Vegetables

The application of EW in the preservation of fruits and vegetables is a topic of growing importance, particularly as consumers increasingly seek fresh produce in its raw form. The authors in [24] reported that food poisoning is caused by pathogens in fruits and vegetables such as strawberries, cantaloupes, spinach, fruit salads, celery, lettuce, and tomatoes. Recent studies examining the effectiveness of EW on various fruits and vegetables demonstrate its significant potential in reducing microbial load [25–28]. The authors in [27] conducted a study focusing on the inactivation of different microorganisms such as *Escherichia coli, Listeria innocua, Pseudomonas fluorescens,* and total viable count, using AlEW (pH of 7.5, ORP pf 890 mV, and free chlorine concentration of 720 ppm). Their findings suggest that this strategy could significantly reduce the risk of foodborne illnesses while simultaneously improving the overall quality and safety of fresh produce such as *Eruca vesicaria, Brassica rapa*, and *Beta vulgaris*. In addition, the authors in [28] found that prolonging the contact time from 30 min to 2 h resulted in an additional reduction of 0.8 log CFU/g inactivation, highlighting the significant advantage of extended contact time. Table 1 provides a summary of the improvements attained by applying various types of EW to fruits and vegetables. As a nonthermal technology, EW can be utilized to enhance the safety and quality of these products. It effectively removes pesticide residues and microbial contaminants from the surfaces of fruits and vegetables (Ali et al., 2024) [45, 46]. However, there are reports indicating that treatment with EW can lead to the accumulation of chlorination byproducts, including chlorates in vegetables. These byproducts pose potential health risks, as prolonged exposure to chlorates has been associated with toxic effects in humans and animals [47]. In addition, studies have shown that EW can generate pesticide transformation products that may be more hazardous than the original pesticides. For instance, research by Studziński et al. [48] found that certain pesticides, when treated with EW, transformed into more toxic metabolites, raising concerns about food safety. These issues are not limited to EW alone; the use of chlorine compounds or other oxidizing agents can similarly facilitate the formation of undesirable byproducts. Kudlek [49] highlighted that such agents can contribute to the production of harmful chlorination byproducts, further complicating the safety of disinfection technologies employed in agriculture and food processing. Therefore, it is essential for researchers to optimize EW processes, balancing their effectiveness in pesticide removal with the potential negative consequences related to byproduct formation.

Also, it preserves the nutrients, color, and texture of fruits and vegetables. EW in combination with ultrasound can prolong shelf life and improve postharvest storage quality and sterilization of fruits and vegetables [45]. EW is acknowledged as a prospective antibacterial agent, albeit with inherent constraints that can be ameliorated through synergistic integration with sonication. It can be used to improve the safety of agri-products and enhance the storage life of fruits and vegetables. Also, it will decrease production degradation and play a pivotal role in achieving food security [50]. Application of NEW and sodium hypochlorite was found effective on endive, carrots, iceberg lettuce, corn salad, and four seasons' salad. Baby spinach leaves were treated with EW [51]. Li et al. [52] investigated and found that AcEW (pH of 2.34, ORP of 1170 mV, and

Table 1: Effect of different electrolyzed water on quality attributes of fruits and vegetables.

Food matrices	Type of EW	Treatments	Time	Characteristics of EW	Major results	References
Lettuce	NEW	Dipping	5 min	ORP: −560 mV pH: 8.51 ACC: 12.34 ppm	Remotion of biofilm cells and destruction of the biofilm structure of *L. monocytogenes*	[1]Shi et al. [29]
Leafy green vegetables	AlEW	Dipping	5 min	ORP: 890 mV pH: 7.5 ACC: 80–150 ppm	Inactivation of *E. coli*, *L. innocua*, and *P. fluorescens*	[1]Shang et al. [27]
Carambola fruit	sAEW	Dipping	10 min	ORP: 1340 mV pH: 6 ACC: 80 mg/mL	Maintaining the nutritional and bioactive compounds and improving storage properties	[1]Zhang et al. [28]
Fresh jujube	AcEW	Washing	10 min	ORP: 1550 mV pH: 2.8 ACC: 90 mg/mL	Maintaining high levels of nutrients and taste compounds and preserving the color.	[2]Chang et al. [25]
Fresh jujube	AcEW	Washing	10 min	ORP: 1550 mV pH: 2.8 ACC: 90 mg/mL	Maintaining cell membrane integrity and the high antioxidant capacities	[2]Chang et al. [30]
Tropical fruits	NEW	Dipping	10 min	ORP: 850 mV pH: 7 ACC: 12, 33, and 53 mg/mL	Eliminating the spore germination of postharvest fungi common in fruits.	[1]Vásquez-López et al. [31]
Chinese bayberries	sAEW	Dipping	45 min	ORP: not reported pH: 5.5 ACC: 50 mg/mL	Preserving the quality features during postharvest storage.	[1]Suo et al. [32]
Eggplant and cucumber	sAEW	Spaying	3 min	ORP: not reported pH: 5.5 ACC: 25 mg/mL	Improving the greenhouse environment by increasing relative humidity.	[2]Bhakta et al. [33]
Buckwheat sprouts	sAEW	Dipping		ORP: not reported pH: 5 ACC: 10.94 mg/mL	On Day 7, enhancing health-promoting benefits and best accumulation of the bioactive substance	[1]Hao et al. [34]
Fresh-cut apples	AcEW	Dipping		ORP: 1000 mV pH: 3.54 ACC: 10.94 mg/mL	Suppressing the bacterial growth during the storage period and maintaining the color	[1]Plesoianu et al. [35]
Fresh organic broccoli	LcEW	Dipping	3–10 min	ORP: not reported pH: not reported ACC: 4 mg/L	Increased sensory quality, antioxidant capacity, reduced microbial load, and a reduction in aerobic bacteria, molds, and yeasts	[1]Liu et al. [36]
Broccoli sprouts	AcEW	Dipping	10–60 min	ORP: not reported pH: not reported ACC: not reported	Prolonging shelf life and reducing aerobic count, molds, and yeast populations	[1]Puligundla et al. [37]
Fresh-sliced button mushrooms	LcEW	Dipping	3 min	ORP: 514.67 pH: 5.50 ACC: 16.86 mg/L	Prolonging the shelf life, delaying surface browning, and reducing yeast and molds	[1]Wu et al., 2018
Watermelon seeds	sAEW	Germination in soaked cotton	—	ORP: not reported pH: not reported ACC: not reported	Enhanced rate of germination, soluble sugar, SOD, POD, and CAT activities; increased GA to ABA ratio; and decreased H_2O_2 and O_2 contents	[1]Wu et al., 2022

Table 1: Continued.

Food matrices	Type of EW	Treatments	Time	Characteristics of EW	Major results	References
Sweet cherry	EW	Dipping	3 min	ORP: not reported pH: not reported ACC: not reported	Physicochemical characteristics (pH, total soluble solids, water activity, weight loss, hardness, color, and anthocyanin profile) are maintained.	[2]Hayta and Aday, 2015
Longan fruit	AcEW	Dipping	10 min	ORP: not reported pH: 2.5 ACC: 0–120 mg/L	Preserving nutrients and bioactive substances, such as pericarp carotenoid, sucrose, flavonoid, chlorophyll, anthocyanin, pulp TSS, and total soluble sugars.	[2]Chen et al. [38]
Blueberries	AcEW	Dipping	5 min	ORP: 1125 mV pH: 2.8 ACC: 48 mg/L	Fruit softness and degradation were prevented by AEW, and its high anthocyanin and total phenolic content were maintained.	[2]Chen et al. [39]
"Valencia" late oranges	AcEW	Applied to fruit wound	—	ORP: 1410–2300 mV pH: 2.6–5.8 ACC: > 100 ppm	Orange quality (mass loss, TSS, citric acid, pH, ascorbic acid, and fruit color index) was unaffected by AlEW and AEW.	[1]Youssef and Hussien [40]
"Valencia" late oranges	AlEW	Applied to fruit wound	—	ORP: −240 to −156 mV pH: 9.2–11.0 ACC: 2.6 ppm	Orange quality (mass loss, TSS, citric acid, pH, ascorbic acid, and fruit color index) was unaffected by AlEW and AEW.	[1]Youssef and Hussien [40]
Coriander	sAEW	Dipping	1–7 min	ORP: not reported pH: not reported ACC: 200 ppm	Bacteria could be efficiently controlled by sAEW	[1]Jiang et al. [41]
Pineapples	EOW	Dipping	10 min	ORP: not reported pH: not reported ACC: 100 ppm	EOW greatly reduced the rate of degradation and extended shelf life by 20 days.	[1]Khayankarn et al. [42]
Sweet potato tuberous root	sAEW	—	10 min	ORP: 800–900 pH: 6.5–6.7 ACC: 80 mg/L	*R. stolonifer* growth was effectively restrained by sAEW.	[1]Li et al. [43]
Jujubes	sAEW	Soaking	5 min	ORP: 922 pH: 5.945 ACC: 80 mg/L	The storage quality has increased with sAEW.	[1]Li et al. [44]

[1]Results obtained on a laboratory scale.
[2]Results obtained on a pilot scale.

51 ppm ACC) and sAEW (pH of 5.9, ORP of 922 mV, and 80 ppm ACC) treatment significantly reduced microbial growth (bacteria, yeast, and mold) during the storage of fresh-cut eggplant. The study conducted by the authors in [52] demonstrates that treatments employing both AcEW and sAEW, distinguished by elevated ORPs and concentrations of ACC, adeptly inhibited microbial proliferation, encompassing bacteria, yeast, and mold, in fresh-cut eggplant throughout the storage period. In a related study [53], documented that the application of sAEW, with a concentration of 50 ppm ACC, notably diminished 4 log CFU/g *Salmonella* contamination in lettuce. The findings underscore the importance of elevated chlorine content, as exemplified by the significant reduction in microbial contaminants achieved through the application of solutions with high concentrations of ACC.

Ding et al. [54] reported that the presence of bacteria, yeast, and molds in strawberries and tomatoes was significantly reduced upon exposure to sAEW (with a pH of 6.49, ORP of 854 mV, and 34 ppm ACC), coupled with ultrasonic (US) treatment (40 kHz, 240 W, 10 min). Notably, the US treatment did not influence the ACC, pH, or ORP of the sAEW solution. Moreover, the study revealed that ultrasound augmented the sterilization efficacy of sAEW, with cherry tomatoes exhibiting heightened responsiveness to US treatment in terms of firmness. These findings collectively suggest that the combination of sAEW and ultrasound represents a promising approach to enhancing food safety. The authors in [55] observed that the application of AcEW (with a concentration of 15, 30, 50, and 80 mg/L ACC) effectively minimized microbial proliferation on the surface of fermented olives, without inducing any visible alterations. When combined with UV-C radiation (0–4770 mJ/cm2), the findings underscore the efficacy of UV-C in diminishing the initial microbial load (aerobic bacteria, yeast, and mold) on surfaces without eliciting any discernible sensory changes across all administered doses. Moreover, the study highlights that as UV-C doses escalate, the rate of reduction in microbial count proportionally increases. Notably, all chlorine concentrations present in AcEW solutions demonstrated effectiveness in reducing surface microbial loads compared to the control group. However, while no significant variance was observed among chlorine concentrations concerning microbial reduction, exceptions were noted for yeast and mold counts.

In a study in [56], researchers investigated the effectiveness of combining sAEW with 0.5% w/v fumaric acid (FA) and calcium oxide (CaO) to disinfect fresh fruits such as apples, mandarins, and tomatoes on an industrial scale. The combined treatments significantly reduced the natural microbiota on fruit surfaces, maintaining good sensory quality during refrigerated storage. In laboratory tests, the treatments also successfully reduced foodborne pathogens such as *Escherichia coli* O157:H7 and *Listeria monocytogenes* by 2.85–5.35 log CFU/g of fruit. Particularly, CaO followed by SAEW + FA treatment showed the highest reduction compared to SAEW + FA alone. This technology has been implemented in the fresh fruit industry in Korea, significantly enhancing product quality. The results indicate that combining SAEW, FA, and CaO could serve as an effective sanitizer in the fresh fruit industry. The authors in [28] examined the impact of sAEW (pH of 6.0, ORP of 1340 mV, and 80 ppm ACC) on postharvest quality and safety of carambola fruit. Remarkably, sAEW demonstrated the potential to decrease respiration rates, enhance cell membrane permeability, inhibit microbial growth, and maintain color integrity. Nutritional composition and bioactive compounds (flavonoids, reducing sugars, polyphenols, Vitamin C, sucrose, total soluble sugar, and total soluble solids) remained largely unaffected, contributing to high acceptability, improved firmness, and minimal weight loss [28].

Likewise, Santo et al. [57] evaluated the influence of AcEW and NEW treatments on infected fresh-cut mangoes. The authors in [58] investigated the effect of washing with sAEW, FA, calcium dioxide, and US mechanical treatment on *E. coli* O157:H7 and *L. monocytogenes* decontamination on tomato and apple fruits. The authors in [59] evaluated the quality of red–yellow fresh-cut bell peppers significantly affected by sAEW and other treatments such as antioxidants and FA. The authors in [60] reported that pathogens in avocados were inhibited by the effect of sodium hypochlorite in NEW. The authors in [25, 30] addressed the challenge of postharvest rapid deterioration in Huping jujube and jujube fruits attributing it to a strong metabolic system and nutritious nature. AcEW in combination with a high-voltage electrostatic field (HVEF) improved storage quality. These treatments improved taste by retention of nutrients and extending the shelf life of fruits [25, 30]. Combined treatments had significant effects on preserving the quality of Huping jujube and jujube fruits.

EW finds utility across diverse food matrices, upholding the standards of food quality and safety, with minimal discernible impact on sensory characteristics [10]. Lopes et al. [61] reported that the microbial attack on fresh-cut mangoes declined with the application of NEW, whereas nutrition evaluation shows that Vitamin C, phenolic compounds, and carotenoids were preserved with treatment. The authors in [62] reported that EW concentration greater than 200 mg/L does not have a positive impact on the sensory quality of sweet cherry, while below this concentration with atmosphere packaging prolongs the shelf life of the fruit. The authors in [32, 50] investigated the storage quality of postharvest Chinese bayberry fruit using US and sAEW. The combination of US and sAEW treatment was effective in preserving the quality of Chinese bayberry fruits. The treatment reduced weight loss and color deviations, retained hardness, and increased the sugar–acid ratio. It also increased the activities of phenylalanine ammonia-lyase, superoxide dismutase, and catalase enzymes, while suppressing polyphenol oxidase activity and malondialdehyde synthesis. The treatment preserved the total phenolic, anthocyanin, and antioxidant levels in the Chinese bayberry fruit. Furthermore, the combined treatment was more effective than either treatment alone in delaying the softening of jujube fruit, maintaining cell membrane integrity, and enhancing antioxidant capacity.

Nyamende et al. [63] highlighted the challenges related to the nutritional and microbiological quality of fresh-cut fruits and vegetables, which often experience softening and browning due to enzymatic activities. Pennywort (*Centella asiatica*), a popular raw green vegetable, was discussed by the authors in [64] as a potential source of foodborne illnesses. A combination treatment involving AcEW at a pH of 2.5 and pulsed light at a dosage of 1.5 J/cm^2 was employed. Notably, the epidermal cells of pennywort exhibited an intact cell structure following the application of a combination of these treatments. This combined treatment demonstrated efficient preservation of the bioactive phytocompounds present in pennywort leaves, particularly triterpene glycosides such as asiaticoside, madecassoside, asiatic acid, and madecassic acid. Furthermore, the treatment enhanced the activities of key enzymes, including phenylalanine ammonia-lyase, superoxide dismutase, and catalase. Simultaneously, it suppressed the activities of polyphenol oxidase and the synthesis of malondialdehyde. In addition, the treatment effectively maintained the levels of total phenolic compounds, anthocyanins, and antioxidants in the leaves.

Bhakta et al. [33] demonstrated that sAEW possesses strong bactericidal properties and is comparatively safer than other disinfectants such as sodium hypochlorite, hydrogen peroxide, and chlorine dioxide, particularly against *Escherichia coli* and *Bacillus subtilis*. In a greenhouse setting, sAEW application at a chlorine concentration of approximately 30 mg/L significantly reduced the viability of airborne microorganisms without adversely affecting the growth of eggplant and cucumber plants. Airborne microorganisms, which include bacteria, fungi, and viruses, can be transported over distances by air currents and originate from sources such as soil, water, vegetation, animals, and human activities. These microorganisms are involved in various processes, including disease transmission, environmental interactions, and agricultural practices. Furthermore, sAEW did not impact microorganisms present in the soil or on the surfaces of plant leaves. In addition, sAEW has the potential to replace tap water, enhancing daytime relative humidity and thereby promoting increased photosynthesis [33].

Diverse studies reviewed collectively suggest that EW, particularly in slightly acidic forms, holds significant promise for enhancing the safety, shelf life, and quality of various fruits and vegetables. The authors in [35] investigated the impact of different solutions (2% citric acid, 0.2% benzoic acid, 0.2% sorbic acid, 0.5% ascorbic acid, and AcEW) on the quality characteristics of fresh-cut apples. It was found that AcEW reduced the enzymatic browning and microbial load as compared to other treatments. The authors in [65] investigated the effect of sAEW (6.25 pH) combined with hydrogen-rich water (394 ppb) on the antioxidants of fresh-cut kiwi fruit. Furthermore, these treatments could elevate the DPPH potential of fresh-cut kiwi fruit with good texture. The authors in [31] investigated the antifungal aspect of NEW to prevent spore-forming of postharvest fungi commonly found in fruits. The authors in [40] evaluated the impact of AlEW and AcEW using four different salts (potassium sorbate, sodium metabisulfite, NaCl, and potassium carbonate) on the decontamination of *Penicillium* species. These treatments have no negative influence on the "Valencia" sweet orange quality. The effect of pulsed light combined with AcEW was determined on the quality characteristics of pennywort leaves during storage. Moreover, it was found that the combination of AcEW and pulse electric treatments is helpful in retaining the sensory properties and bioactives in pennywort leaves. The AcEW has shown inadequate efficacy on food products, utensils, and surfaces [8]. Some studies have reported using EW instead of tap water in legumes and cereals such as buckwheat, mung beans, brown rice, and alfalfa for soaking and germination [66, 67].

The growing body of research on EW applications in the preservation of fruits and vegetables emphasizes its potential as a nonthermal, eco-friendly alternative to traditional chemical sanitizers. EW, particularly in its slightly acidic form (sAEW), has been shown to effectively reduce microbial contamination and prolong shelf life without compromising the sensory qualities of the produce [28, 63]. This makes it an attractive option for ensuring food safety, especially as consumers increasingly demand minimally processed and pesticide-free products. However, while the benefits of EW are well-established, challenges remain. One notable concern is the formation of harmful byproducts such as chlorates and pesticide transformation products, which can pose health risks when ingested in significant quantities [47, 48]. This raises questions about the balance between its microbial efficacy and potential negative impacts on food safety. Future research should focus on optimizing EW treatment parameters, such as contact time and chlorine concentration, to minimize byproduct formation while maintaining its disinfectant properties [28]. Furthermore, combining EW with other technologies, such as ultrasound or HVEFs, has shown promise in enhancing its antimicrobial effectiveness [25]. These synergies not only improve food safety but also preserve critical attributes such as color, texture, and nutritional value. Such integrated approaches could provide a more robust solution to postharvest preservation, particularly for delicate fruits and vegetables prone to spoilage. From an industrial perspective, the scalability and cost-effectiveness of EW treatments need further exploration. While laboratory-scale studies demonstrate promising results, large-scale implementation in commercial food processing requires careful consideration of equipment, cost, and regulatory approvals. In addition, the long-term effects of EW on food quality, especially during extended storage, remain underresearched. In conclusion, while EW presents a sustainable and effective solution for improving the safety and quality of fruits and vegetables, there are still challenges that must be addressed. Further studies are needed to optimize its use and ensure that it can be safely and effectively applied on an industrial scale without compromising food safety. This will be crucial in its adoption as a mainstream technology for enhancing food security and reducing foodborne illnesses.

4. EW in Meat and Meat Products

The innovative application of electrolysis technology is also viable in the meat industry. EW can be utilized for the direct treatment of meat and meat products [68–70], as well as for sanitizing tools, machinery, and surfaces that come into contact with meat during production [10, 71, 72]. Table 2 summarizes the advancements achieved in recent years through the application of various types of EW in the processing and preservation of meat and meat products.

4.1. EW in Fresh Pork Meat and Pork Meat Products. Pork meat is one of the most significant and widely produced types of meat worldwide. Its consumption has increased to 55.95 million tons in 2018 [97]. However, pork meat is susceptible to deterioration owing to its elevated levels of protein, fat, and moisture [98]. Besides oxidation, microbial contamination stands as the major contributor to pork meat spoilage [99]. Consequently, numerous studies have been conducted to assess the effectiveness of EW treatment on fresh pork and pork-based products.

Fresh pork was decontaminated with the application of low-concentration EW (LcEW) [74, 75] and low-concentration acidic EW (LcAEW) [73] with effectiveness against *E. coli, L. monocytogenes,* and *Campylobacter coli.* The risk associated with microbial contamination increases even more when considering ground pork meat, which has a larger surface area exposed to air and a more complex surface morphology.

Following 10 min of electrolysis, NEW (with an ACC concentration of 29 mg/L) demonstrates complete eradication of *Escherichia coli*, both in suspension and within contaminated ground pork. However, the bactericidal efficacy of NEW on ground pork is comparatively diminished in contrast to suspension, attributable to the intricate surface morphology of ground pork, which serves as a physical hindrance against the antibacterial effects of NEW. Upon 20 min of electrolysis, NEW (with an ACC concentration of 51 mg/L) achieves a reduction of only 1.77-log CFU/g of *Salmonella enterica*. Consequently, the application of NEW for treating *Salmonella enterica* present in pork meat exhibits limited practical utility. This discrepancy in outcomes between *Escherichia coli* and *Salmonella enterica* treatments is attributed to the capability of *Salmonella enterica* to form biofilms [77]. Moreover, the application of 0.01% NaCl-based EW sprayed on fresh pork meat has significantly reduced microbes particularly inhibiting the growth of *Pseudomonas fluorescens* [100].

With the aim of reducing the volumes of EW required for the treatment, the authors in [78] compared the effects of spraying sAEW, strongly basic EW (BEW) and the combination of the two on pork loins. The combination of the two types of EW exhibited the maximum antimicrobial effect, compared to the use of the individual types, reducing the count of mesophilic and psychrotrophic bacteria during refrigerated storage. Conversely, neutral EOW (NEOW) has been empirically established as an antimicrobial agent effective in reducing the incidence of pathogenic microorganisms, including *E. coli*, *Yersinia enterocolitica*, and *Salmonella*, in pork chops, with heightened efficacy observed in pork skin [79]. Moreover, spraying with NEW demonstrated a high antibacterial activity against *L. monocytogenes* in heavily contaminated pork chops (artificially contaminated with an inoculum of 10^6 CFU/mL) [80]. Regarding lipid oxidation, although the use of NEW resulted in an increase in thiobarbituric acid reactive substances (TBARS) concentration, it remained within 2 mg MDA/kg, known as the acceptable limit for human consumption [101]. Conversely, other studies observed a reduction in the degree of lipid oxidation resulting from EW treatment during the storage of fresh pork. In the study of [74], untreated pork samples exhibited an escalating trend in lipid oxidation throughout storage, whereas samples treated with LcEW and calcium lactate displayed a comparatively attenuated rate of lipid oxidation during the storage period.

The study conducted by the authors in [81] aimed to compare the treatment with AlEW with traditionally employed treatments (salt/phosphate-based solutions) to enhance the water-holding capacity and palatability characteristics of pork loins. However, the use of AlEW did not improve the water-holding capacity, tenderness, or sensory characteristics (tenderness, juiciness, pork flavor, and off-flavor) of the treated pork loins. Only the addition of potassium lactate to AlEW leads to better results achieved in moisture retention and sensory characteristics, albeit traditional treatments proved to be more effective.

4.2. EW in Poultry Meat. Typically, whole chicken carcasses exhibit microbial counts exceeding 4.5 log CFU/g [102]. This can be attributed to the various procedures involved in the slaughtering process (defeathering, evisceration, washing, and chilling), which can lead to cross-contamination of carcasses with bacteria. Therefore, minimizing microbial contamination on carcasses is crucial during processing in slaughterhouses to delay meat deterioration and extend its shelf life. The most employed products for decontamination in slaughterhouses are chlorine-based disinfectants, such as sodium hypochlorite and chlorine dioxide. However, the use of this disinfectant poses potential risks, as highlighted by recent studies demonstrating the production of carcinogenic substances and mutagenic chlorinated compounds through reactions with organic molecules [6]. Consequently, some research efforts have focused on finding a substitute for sodium hypochlorite for the poultry industry. Several studies suggested that spraying or washing chicken carcasses with EOW exhibits antimicrobial efficacy equal to or, in some cases, greater than other commonly employed antimicrobial treatments in the poultry meat industry, such as sodium hypochlorite treatment. This is observed against various foodborne pathogens, including *S. Typhimurium*, *E. coli*, and *Campylobacter* spp [82, 83, 103]. Moreover, beyond its effective control of pathogenic microorganisms, EOW has proven to be a viable alternative to chlorine-based products, even for managing spoilage-causing microflora [84]. Chicken carcasses were sprayed for 5 s at 80 psi with tap water, chlorinated water, and EOW. Subsequently, the

Table 2: Effect of different electrolyzed water on quality attributes of meat and meat products.

Food matrices	Type of EW	Treatments	Time	Characteristics of EW	Major results	References
Fresh pork meat	LcAEW	Spraying	120 s	ORP: 1159.32 mV pH: 2.15 ACC: 16.60 $mg \cdot L^{-1}$	Reduction in the total number of microorganisms (3.25 log reduction), yeast and molds (2.68 log reduction) and psychrotrophs (3.10 log reduction)	[1]Brychcy et al. [73]
Fresh pork meat	LcEW + 3% calcium lactate	Dipping	5 min	ORP: 700–720 mV pH: 6.8 ACC: 10 mg/L	Reduction of *Escherichia coli* O157: H7 and *Listeria monocytogenes*	[1]Rahman et al. [74]
Fresh pork meat	LcEW	Dipping	10 min	ORP: 700 mV pH: 6.8 ACC: 10 mg/L	Reduction of L. *monocytogenes* of 1.72–1.74 log	[1]Wang et al. [75]
Fresh pork meat	sAEW	Dipping	3 min	ORP: 826 mV pH: 6.29 ACC: 30 mg/L	Reduction of *E. coli* O157:H7, *L. monocytogenes*, *Staphylococcus aureus*, and *Salmonella Typhimurium*	[1]Mansur et al. [76]
Ground pork meat	0.85% NaCl NEW 10 min electrolysis	Shaken continuously	5 min	ORP: 425 mV pH: 9.09 ACC: 29.14 ppm	Reduction 7 log CFU/mL of *E. coli* and 2 log CFU/mL of *S. enterica*	[1]Nguyen et al. [77]
Fresh pork meat	0.01% NaCl-AcEW	Spraying	60 s	ORP: 1049.8 mV pH: 2.73 ACC: 8.45 ppm	Reduction of yeasts and mold count	[1]Brychcy et al. [73]
Fresh pork meat	sAEW + BEW	Spraying	20 s sAEW 20 s BEW	ORP: 1200 (sAEW) −830 (BEW) mV pH: 2.60 (sAEW) 11.40 (BEW) ACC: 74 (sAEW) 0 (BEW) ppm	Reduction of the count of mesophilic and psychrotrophic bacteria during refrigerated storage	[1]Athayde et al. [78]
Pork skin and chops	NEOW	Dipping	2 min	ORP: 818 mV pH: 7.64 ACC: 0.74 ppm	Reduction of pathogenic microorganisms, including *E. coli*, *Yersinia enterocolitica*, and *Salmonella*	[1]han et al. [79]
Pork chops	NEW	Spraying	60 s (in contact with meat)	ORP: 820 mV pH: 6.92 ACC: 58 ppm	Antibacterial activity against *L. monocytogenes*	[1]Torres-Rosales et al. [80]
Fresh pork meat	LcEW + 3% calcium lactate	Dipping	5 min	ORP: 245 mV pH: 6.82 ACC: 1 mg/L	Reduction of the surface microbial counts immediately after the treatment and lag in microbial growth and in lipid oxidation during storage	[1]Rahman et al. [74]
Pork loins	AlEW + potassium lactate	Multineedle injection	—	ORP: 187 mV Ph: 11,76 ACC: not reported	Improvement in water-holding capacity and sensory characteristics, although less than traditional treatments	[2]Rigdon et al. [81]

Table 2: Continued.

Food matrices	Type of EW	Treatments	Time	Characteristics of EW	Major results	References
Chicken carcasses	AEOW	Washing	10 s	ORP: 1180 mV pH: 2.4 ACC: 50 mg/L	Reduction of the levels of total aerobic bacteria (6.1 vs. 5.8 log10 cfu/mL), *E. coli* (4.6 vs. 4.1 log10 cfu/mL), *Campylobacter* (5.2 vs. 4.2 log10 cfu/mL), and *Salmonella* (2.0 vs. 1.2 log10 cfu/mL)	[2]Northcutt et al. [82]
Chicken carcasses	AEOW + sAEOW	Spraying	15 s	ORP: 1126 (AEOW) 865 (sAEOW) mV pH: 2.46 (AEOW) 5.98 (sAEOW) ACC: 58 (AEOW) 30 (sAEOW) mg/L	Reductions of 0.47–0.83 log CFU/cm^2 and 0.49–0.96 log MPN/cm^2 in TVC and total coliforms	[2]Duan et al. [83]
Chicken carcasses	AEOW	Spraying	5 s	ORP: +1180 mV pH: 2.4 ACC: 50 ppm	Immediately after treatment and after 14 days of storage, lower psychrotrophic bacteria and yeast count were observed compared to other treatments	[1]Hinton Jr. et al. [84]
Chicken carcasses	AcEW or sAEW	Spraying	15 s	ORP: 1150 (AEW) 845 (sAEW) mV pH: 2.55 (AEW) 6.00 (sAEW) ACC: 60 (AEW) 30 (sAEW) mg/L	Microbial reduction of almost 1.0 log CFU/cm^2 or MPN/cm^2	[3]Wang et al. [85]
Chicken carcasses	NEW	Dipping	1.5 h	ORP: 1.123 mV pH: 6.5 ACC: 50 mg/L	Reduction of the total viable count and coliforms by damaging the membranes, without changes in color and pH	[1]Hernández-Pimentel et al. [86]
Chicken breast	NEW + peroxyacetic acid	Dipping	10 min	ORP: 830 mV pH: 6.8 ACC: 800 μg/mL	Lower numbers of aerobic bacteria, psychrophiles, Enterobacteriaceae, lactic acid bacteria, and *Pseudomonas;* lower lipid oxidation and highest score in sensory attributes, compared to the other treatments	[1]Moghassem Hamidi et al. [87]
Chicken breast	NEW	Spraying	1 min of contact	ORP: 895.67 mV pH: 6.70 ACC: 55.73 ppm	Reduction of 1.2 and 0.33 Log10 CFU/chicken breast in chicken breasts contaminated with *E. coli* and *Salmonella Typhimurium*, respectively, after 8 days of storage; no effects in the appearance, odor, and texture evaluated in a sensory test	[1]Rosario-Pérez et al. [88]

Table 2: Continued.

Food matrices	Type of EW	Treatments	Time	Characteristics of EW	Major results	References
Raw chicken legs	sAEW	Dipping	From 2 to 5 times for 15 min with a sAEW: meat ratio of 4:1.	ORP: 890–910 mV pH: 5.8–6.2 ACC: 30–33 ppm	Reduction of the bacterial load, lower total volatile basic nitrogen and lipid oxidation after 0 or 3 days of storage, and increase of meat brightness	[1]Kartikawati et al. [89]
Frozen beef	sAEW	Immersion at ± ° 1 C	Until the reach of a core temperature of 0°C	ORP: not reported pH: not reported ACC: not reported	Inactivation of the total bacteria, fungi, and yeasts by 1.76 logs; no detrimental effects on the physicochemical and sensory attributes; and retardation of lipid and protein oxidation.	[1]Liao et al. [90]
Frozen mutton	sAEW + ultrasound	Ultrasonic bath containing 12.5 L sAEW.	Until the sample temperature reached 4°C	ORP: 889.67 ± 2.08 mV pH: 5.29 ± 0.01 ACC: 42.67 ± 0.58 ppm	Inhibition of lipid oxidation, no nutrient loss during the thawing process, preservation of superior structural properties and microstructure, and reduction of water migration.	[1]Kong et al. [91]
Fresh beef	sAEW	Dipping	5 min	ORP: 870–900 mV pH: 6.29 ACC: 40 ppm	Extension of the shelf life by 8 days at 4°C; no differences in thiobarbituric acid content.	[1]Sheng et al. [92]
Fresh beef	sAEW + tea polyphenols	Immersion	2.5 min + 2.5 min	ORP: 655.4 mV pH: 6.51 ACC: 30 mg/L	Decreased microbial populations and reduced lipid oxidation during the storage of fresh beef, extending the shelf life by approximately 9 days at 4°C.	[1]Bing et al. [93]
Goat meat	Ozonated water + AlEW	Dipping	4 min + 4 min	ORP: −421.3 mV pH: 11.03 ACC: 0.06 ppm	Reduction (1.03 CFU/mL) of *E. coli* K12 population on the meat surface	[1]Degala et al. [94]
Piedmontese tartare	EW	Immersion	90 s	ORP: 735–740 mV pH: 8.55 ACC: 100 ppm	Initial surface decontamination is no longer detectable in the ground meat.	[2]Botta et al. [95]
Low-sodium mortadella	BEW	Addition	—	ORP: 92.33 mV pH: 10.99 ACC: 1.2 mg/L	Increase of pH and decrease of redox potential and of the development of lactic acid bacteria	[1]Leães et al. [96]

[1]Results obtained on a laboratory scale.
[2]Results obtained on a pilot scale.
[3]Results obtained on an industry scale.

treated carcasses were stored at 4°C for 0, 3, 7, and 14 days, and the populations of psychrotrophic bacteria and yeasts on the carcasses were enumerated. The results indicated that both immediately after treatment and during the storage period, a significantly lower number of psychrotrophic yeast and bacteria were recovered from carcasses sprayed with EOW compared to the other treatments.

Evidence of effectiveness also exists for other types of EW. Spraying with AcEW or sAEW for 15 s resulted in a microbial reduction of almost 1.0 log CFU/cm^2 or MPN/cm^2 on chicken carcasses [85]. Dipping of chicken carcasses in NEW (100 L containers for 1.5 h) reduced the total viable count and coliforms by damaging the membranes, without inducing changes in meat color and pH during a 10-day storage period [86]. No trihalomethanes were detected in meat using 50 mg/L of NEW, whereas exceeding 100 mg/L, only 0.037 mg/kg of chloroform was detected.

Rosario-Pérez et al. [88] compared the effects of spraying NEW and sodium hypochlorite on chicken breasts during chilled storage. The treatment with NEW showed a bacterial reduction of 1.2 and 0.33 Log10 CFU/g in chicken breasts contaminated with *E. coli* and *S. Typhimurium*, respectively, after 8 days of storage in a plastic bag at 4°C. Otherwise, sodium hypochlorite treatment did not lead to bacterial reduction. Both treatments did not increase lipid oxidation and slowed down meat decomposition caused by biogenic amines. From a sensory perspective, NEW treatment did not affect the appearance, smell, and texture as evaluated in a sensory test. The study conducted by the authors in [88] highlights the potential of NEW in mitigating bacterial contamination on chicken breasts during chilled storage. However, the observed reduction may be insufficient, indicating that NEW alone may not be optimal for chicken breast sanitation. Combining NEW with other technologies, such as ultrasonication, could potentially enhance bacterial reduction logarithms and improve overall efficacy.

Moghassem Hamidi et al. [87] evaluated the effectiveness of NEW and peroxyacetic acid and their combination on the chicken breast during chilled storage. All treatments successfully reduced microbial populations throughout the storage period, with the combined treatment (NEW 100 μg/mL + peroxyacetic acid 200 μg/mL) exhibiting the most potent antimicrobial activity. By the sixth day of storage, the combined treatment resulted in significantly lower plate counts for aerobic bacteria, psychrophiles, Enterobacteriaceae, lactic acid bacteria, and Pseudomonas compared to the control group. Furthermore, at the end of the storage period, the combined treatment not only demonstrated lower lipid oxidation but also received the highest scores for sensory attributes such as odor, texture, and color, surpassing the other treatments.

Kartikawati et al. [89] posited that an increased number of washing sessions (frequency) could potentially mitigate microbial contamination while simultaneously reducing the amount of water required for disinfection. Therefore, their study assessed the effect of immersion in sAEW at various frequencies on the disinfection and quality of raw chicken legs. The results demonstrated that by reducing the amount of water used and increasing the frequency of immersions, a significant decrease in bacterial load was achieved. In addition, the increase in immersion frequency led to a lower concentration of volatile basic nitrogen (under 7 mg/100 g), a lower degree of lipid oxidation after 0 or 3 days of storage, and a higher brightness of meat.

4.3. EW in Beef and Other Meat Products. Thawing is an essential step for subsequent processing in the meat industry. The most common thawing methods include air thawing, water thawing, and microwave thawing. However, this process is slow and uneven, potentially exposing parts of meat to conditions conducive to microbial growth and causing changes in chemical and physical properties [90]. Liao et al. [90] suggested sAEW as a thawing medium to ensure microbiological safety and the quality attributes of beef. Thawing using sAEW efficiently inactivated the total count of bacteria, fungi, and yeasts by 1.76 logs. It did not result in any detrimental effects on the physicochemical (thawing loss, cooking loss, colorimetric parameters, and texture) and sensory attributes (color, odor, texture, and overall acceptability) and delayed lipid and protein oxidation in beef differently from the conventional thawing methods. These outcomes were corroborated by the study conducted by the authors in [91], which investigated the impact of ultrasound-assisted sAEW thawing on the quality, nutrients, and microstructure of mutton. The treatment not only effectively inhibited lipid oxidation in the samples but also prevented nutrient loss during the thawing process. Texture profile analysis and low-field nuclear magnetic resonance demonstrated that this method could preserve superior structural properties and reduce water migration in the samples, resulting in a thawed state more akin to that of fresh meat. Furthermore, the microstructure of meat was more intact and compact compared to samples thawed using conventional methods.

Sheng et al. [92] examined the effects of sAEW on the microbiological, physicochemical, and sensory characteristics of fresh beef during the storage period. Moreover, considering that tea polyphenols have demonstrated bactericidal and antioxidant effects on fresh meat, they were included in the trial for comparative analysis. The treatment with sAEW extended the shelf life of beef by 8 days at 4°C, compared to other treatments. However, no significant differences were observed between the untreated group and the treated group in terms of thiobarbituric acid content, suggesting that the treatment with sAEW lacks antioxidant activity. Following this study [93], we observed that the immersion in sAEW at an ACC of 30 mg/L for 2.5 min followed by the immersion in tea polyphenols at a 0.1% concentration for 2.5 min can decrease microbial populations and reduce lipid oxidation during the storage of fresh beef, extending the shelf life by approximately 9 days at 4°C. Tea polyphenols are widely used as preservatives and antioxidants in the food industry, particularly in the preservation of meat. They play a vital role in protein precipitation and enzyme inhibition and exhibit antibacterial and antioxidative properties [104]. Consequently, tea polyphenols can be employed as antioxidants in conjunction with sAEW to address the antioxidant capacity deficiency of sAEW in meat preservation.

The effects of treatment with EW have also been studied on goat meat, evaluating its application in synergy with ozonated water for the inactivation of *E. coli* K12. The combination of ozonated water and AlEW resulted in higher logarithmic reductions (1.03 CFU/mL) compared to ozonated water alone (0.53 CFU/mL). This suggests that EW, when used in combination with other alternative inactivation methods, can enhance their efficacy [94].

Botta et al. [95] investigated the impact of a pregrinding treatment with EW on the microbiological and physicochemical properties of Piedmontese tartare stored under vacuum packaging at 4°C. Meat immersed in an EW solution containing 100 ppm of free active chlorine for 90 s exhibited initial surface decontamination without significant compositional changes, though there was an alteration in external color. However, this initial decontamination effect was not observed in the ground meat, likely due to the rapid bacterial recovery during the grinding process from the transient oxidative stress induced by the EW.

Efforts by researchers and the meat industry to reduce sodium content in meat products are well-documented. Reducing salt can affect shelf life by altering critical attributes such as texture and color. The authors in [96] investigated the individual and combined effects of BEW (pH 10.99; −92.33 mV) and ultrasound treatment (25 kHz; 175 W; 20 min) on the microbiological and oxidative profiles of low-sodium mortadella (30% reduction in NaCl) stored for 90 days at 5°C. The application of BEW increased the pH and decreased the redox potential, thereby inhibiting the growth of lactic acid bacteria. When combined with ultrasound treatment, the lactic acid bacteria count was reduced by up to 0.36 log CFU/g. Thus, the combined use of ultrasound and BEW shows promise as a strategy to improve the microbiological and oxidative quality of mortadella during storage.

The application of EW in the meat industry presents promising advancements for enhancing food safety, extending shelf life, and improving the quality of meat products. The discussion surrounding its use in fresh pork, poultry, beef, and other meat products highlights its potential to replace traditional sanitizers such as sodium hypochlorite, which have raised concerns due to the formation of harmful byproducts. EW offers a safer, eco-friendly, and effective alternative for microbial decontamination. In pork, EW shows significant efficacy in reducing microbial contamination, particularly for pathogens such as *E. coli* and *Listeria monocytogenes*. However, its limited effectiveness against biofilm-forming bacteria such as *Salmonella enterica* raises concerns about its standalone utility, suggesting a need for complementary technologies or higher concentrations. Similarly, in poultry, EW has demonstrated substantial antimicrobial activity but combining it with other treatments such as ultrasonication could optimize its effectiveness. The preservation of sensory and physicochemical qualities in meat treated with EW is another critical benefit, particularly in reducing lipid oxidation and retaining moisture during storage. This feature supports its integration into meat processing to maintain product quality while ensuring microbial safety. Studies on beef and goat meat suggest that combining EW with other natural preservatives, such as tea polyphenols, or advanced methods such as ultrasound, can further enhance its effectiveness, providing a holistic approach to meat preservation. Nonetheless, challenges remain, including the cost and practicality of large-scale EW implementation and its variable effectiveness depending on meat type, bacteria strains, and treatment methods. While EW can extend the shelf life and safety of meat products, further research is required to optimize its application in conjunction with other preservation techniques. In conclusion, EW represents a transformative solution in meat processing, offering both safety and quality benefits. However, its potential can be maximized through synergistic treatments, which could offer a sustainable and highly effective approach to microbial control in the meat industry.

5. Conclusions

Water electrolysis technology has recently emerged as a highly promising green, emerging sensitizing, nonthermal, and sustainable technical method in a variety of industries, including food. EW offers numerous advantages over traditional disinfection systems, including cost-effectiveness, cleaning agent, removal of pesticide residual, eco-friendly, effective sanitizing agent, antimicrobial potential, ease of application, onsite production, and safety for both humans and the environment. Combination with other technologies (such as sonication, ultrasound, and HVEF) results in prolong shelf life by reducing bacterial load and improving postharvest storage quality, taste, retention of nutrients, increasing sugar–acid ratio, and sterilization of fruits and vegetables. EW has been used to clean cutting equipment, chicken carcasses, eggs, fresh-cut fruit, and sprouts. It has demonstrated potential in terms of preventing microbial development, protecting food quality, and minimizing the need for typical chemical sanitizers. Nonetheless, EW provides a green and sustainable solution to the growing demand for safe and healthy food business practices, and its acceptance is projected to increase as technology and understanding of its applications advance. EW offers food product decontamination by offering antimicrobial benefits and promoting functional component accumulation. Also, it will decrease production degradation and play a pivotal role in achieving food security. Nutritional composition and bioactive compounds (flavonoids, polyphenols, reducing sugars, sucrose, Vitamin C, total soluble sugar, and total soluble solids) remained largely unaffected, contributing to high acceptability, improved firmness, and minimal weight loss when treated with EW. More focus on research and development is required to improve the EW production technology, scalability, efficiency, and reducing energy consumption. Meanwhile, mutual collaboration would be helpful to optimize the EW application in the food sector. Governments, food authorities, regularity, and standard bodies should develop standards, safety guidelines, and application methods in food industries. This will be helpful for consumers' preferences. Moreover, food technologists and professionals should be trained to familiarize themselves with EW technology and its key advantages. Most of the studies conducted to date on the use of EW for food sanitation have been performed on a laboratory scale. Consequently, research is now required at a larger, industrial scale to not only assess the effectiveness of the technology but also to evaluate its feasibility and applicability in real-world processing environments. Further research studies should be conducted to understand the potential application of EW to enhance food safety, quality, nutrition, bioactive compounds, functional properties, product development, antimicrobial effect, consumer preferences, sensory quality, and sanitation in food industries.

Nomenclature

ACC	Available chlorine concentration
AcEW	Acidic electrolyzed water
AlEW	Alkaline electrolyzed water
BEW	Basic electrolyzed water
EOW	Electrolyzed oxidizing water
EPA	Environmental protection agency
EW	Electrolyzed water
LcAEW	Low-concentration acidic electrolyzed water
LcEW	Low-concentration electrolyzed water
NEOW	neutral oxidizing water
ORP	Oxidation-reduction potential
sAEW	Slightly acidic electrolyzed water
TBARS	Thiobarbituric acid reactive substances
WAEW	Weak acidic electrolyzed water

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Parkash Meghwar and Lucrezia Forte: Writing–original draft and conceptualization. Syed Muhammad, Ghufran Saeed, and Slim Smaoui: Writing–review and editing. Pasquale De Palo: Writing–review, editing, and visualization. Aristide Maggiolino: Writing–review and editing, supervision, conceptualization, and visualization.

Funding

No funding was received for this study.

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