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Review

Application of Electrolyzed Water in the Food Industry: A Review

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Abstract: Electrolyzed water is a novel disinfectant and cleaner that has been widely utilized in the food sector for several years to ensure that surfaces are sterilized, and that food is safe. It is produced by the electrolysis of a dilute salt solution, and the reaction products include sodium hydroxide (NaOH) and hypochlorous acid. In comparison to conventional cleaning agents, electrolyzed water is economical and eco-friendly, easy to use, and strongly effective. Electrolyzed water is also used in its acidic form, but it is non-corrosive to the human epithelium and other organic matter. The electrolyzed water can be utilized in a diverse range of foods; thus, it is an appropriate choice for synergistic microbial control in the food industry to ensure food safety and quality without damaging the organoleptic parameters of the food. The present review article highlights the latest information on the factors responsible for food spoilage and the antimicrobial potential of electrolyzed water in fresh or processed plant and animal products.

Keywords: electrolyzed water; decontamination; fruits and vegetables; fish and seafood; meat and poultry; food industries

1. Introduction

Around the globe, numerous foodborne aliments are prevalent [1]. These diseases are costing humans enormous suffering and posing survival challenges over time, and currently, the issues of food intoxication and acute food borne infections are reaching alarming rates in comparison to the past few decades [2], raising concerns for governments, regulatory authorities, and food processing industries [3]. Foodborne diseases caused by the consumption of unsafe food results in 600 million reported cases globally, with an annual death rate of 420,000 people out of 56 million total deaths each year [4]. A total of 600 million individuals suffering from foodborne illnesses account for 7.69% of the total world population (7.8 billion). Each year, 56 million people die due to various reasons, and 7.5% of these mortalities (420,000 death) occur solely due to foodborne diseases.

According to statistics from the World Health organization, 23 million people in Europe suffer from foodborne illnesses with an annual mortality rate of 5000 individuals [5]. According to the data from Centers for Disease Control, in the USA, 1 out of 6 people are affected by the consumption of contaminated food or beverages, with annual death rate of 3000 individuals. As per the calculations of the United States Department of Agriculture, contaminated food and beverages costs more than 15.6 billion US dollars each year [6]. Scientific societies around the globe are continuously striving to establish safe and effective protocols and means to ensure food safety [7]. Food safety issues have always been a point of concern for food manufacturers, retailers, researchers, regularity authorities, and policymakers in developed as well as developing countries [8], such as Japan [9], the USA [10], Taiwan [11] and the United Kingdom [12]. Recent outbreaks in these countries have increased international concerns regarding the issue [13].

To date, numerous techniques have been designed to control incidences of food-borne diseases to ensure the provision of a safe food supply [14]. Most food processing establishments implement Hazard Analysis Critical Control Points (HACCP) in their systems as a preventive measure [15]. Incidences of food-borne illness outbreaks are still prevalent in the foodservice sector, including food stores, institutions, and fast-food restaurants, where food commodities receive multiple treatments to ensure their safety for consumption [16]. Even after implementing safety measures, the incidence of these issues indicates that hazards still exist in the food supply chain [17]. With increasing demands for processed food, the food chain is becoming complicated in terms of transportation, handling, storage, and processing, rendering the maintenance of a safe food supply a challenging task [13].

Another challenge is presented by the current environmental conditions that are increasing the urge to utilize natural resources [18]. To conserve energy and water resources [19], emerging technologies are being developed in an attempt to create reliable alternatives to restrict or eliminate the production of chemical residues produced during various operations [20]. These technologies, alternatives to the conventional methods, attempt to improve microbiological safety, physicochemical characteristics, and overall food quality [21]. Electrolyzed water technology, an invention of green chemistry, has gained popularity as a disinfection technique [22]. Electrolyzed oxidizing water, also regarded as Electrolyzed Strong Acid Aqueous Solution (ESAAS) [23] or Strong Acidic Electrolyzed Water (StAEW), is a novel antimicrobial that has been used globally for the past few years [24]. Numerous studies report the antimicrobial potential of electrolyzed water against a variety of microorganisms [25]. In the recent past, electrolyzed water has found its application in medicine, dentistry [26], agriculture, and the food industry [27]. In the various food industries, electrolyzed water is used as disinfectant for cutting tools, an antimicrobial agent for the carcasses of poultry birds [28], and for disinfecting eggs in the meat industry [29]. In the fruits and vegetable processing industries [30], lettuce [31], pears [32], peaches [33], sprouts [34], apples [35], tomatoes [36], alfalfa seeds [37], strawberries, and their respective forms of processing equipment are disinfected using electrolyzed water [38].

Electrolyzed water is not only inexpensive but is also far more effective than conventional cleaning agents [39]. Electrolyzed water kills pathogenic microorganisms [40] and protects the environment from the adverse impacts of hazardous chemical disinfectants [41]. Figure 1 shows a schematic diagram of electrolyzed water manufacturing. This process creates cheaper, safer, and more effective products compared to dangerous synthetic chemical preservatives such as acetic acid, sodium hypochlorite, and glutaraldehyde [42]. In this review, some of the important characteristics of electrolyzed water will be elucidated, i.e., its antimicrobial, physical, and chemical properties; functional characteristics; and its utilization in food industries such as poultry, fruits and vegetable, egg, and seafood processing.

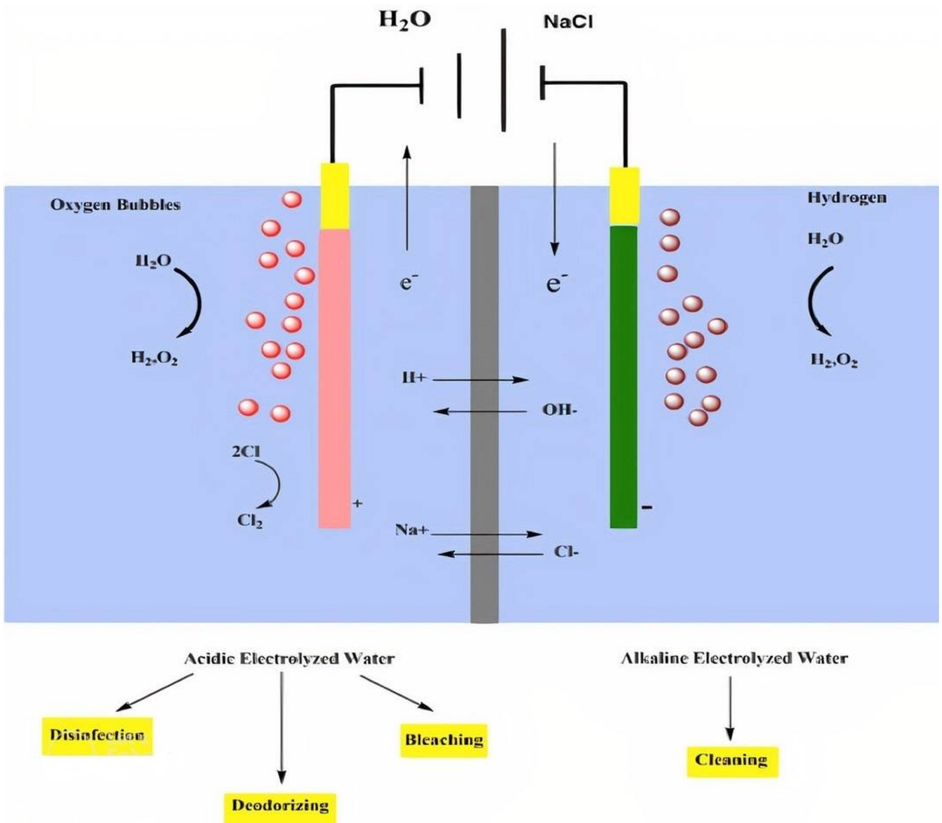

Figure 1. Schematic diagram of electrolyzed water manufacturing.

2. Application of Electrolyzed Water in the Food Industry

The growth and sustainability of microorganisms depend upon the environmental conditions, food composition, storage conditions, and the processes the food undergoes during its keeping life [43,44]. There are two types of driving forces that impact the microbial safety of foods: intrinsic factors and extrinsic factors, i.e., food matrix inherent properties and the surrounding environment (the processing and storage conditions), respectively [45]. The food matrix and its surrounding environment undergo various changes from the time of harvest to consumption, which are considered potential contributors to product development [46]. To endure these changes, each microorganism has its own upper and lower threshold limits [47]. Each microbial species has its own optimum growth conditions in terms of intrinsic and extrinsic factors [48]. These optimum values are neither absolute nor specific; they vary from species to species [49]. When microorganisms grow in a food environment, they adapt to it and acquire essential nutrients required for their canal metabolism and energy synthesis [50]. Besides nutritional requirements, it is also essential to support the atmosphere and temperature [51]. To prevent these microbes from becoming food safety risks, it is important to understand the growth and metabolic requirements of the target spoilage agents [52]. Usually, unfavourable growth conditions are created to inhibit and inactivate pathogenic and food spoilage-capable microorganisms [53].

2.1. Main Factors Responsible for Food Spoilage

To enhance food safety and product quality, intrinsic and extrinsic factors are both naturally and artificially modulated. The adjustments made to these factors/conditions minimize and/or prevent the growth and establishment of microbial flora, which in turn escalates the shelf-life of food [54]. Figure 2 summarizes the factors responsible for food spoilage. The inherent or intrinsic factors include the chemical, physical, and biological makeup of the food matrix, i.e., water activity, pH, moisture content, food composition, redox potential (oxidation-reduction), biological structures, and antimicrobial components [55]. The external or extrinsic factors include a gaseous environment, temperature, the relative humidity, the processing operations, and the presence of other microorganisms [56]. Regulating these extrinsic and intrinsic factors ensures the adequate microbial safety of food [57], as these factors influence microbial growth and resistance [56,57]. Food storage and processing conditions can hinder maximum microbial growth by influencing their metabolic systems, the energy sources of food spoilage, and the proliferation conditions for pathogenic microorganisms [58,59]. These changes in the food system can be induced naturally and artificially to maintain food quality and safety. The advancing knowledge in the field helps predict microbial safety, food stability, and the design of new prevention techniques [60].

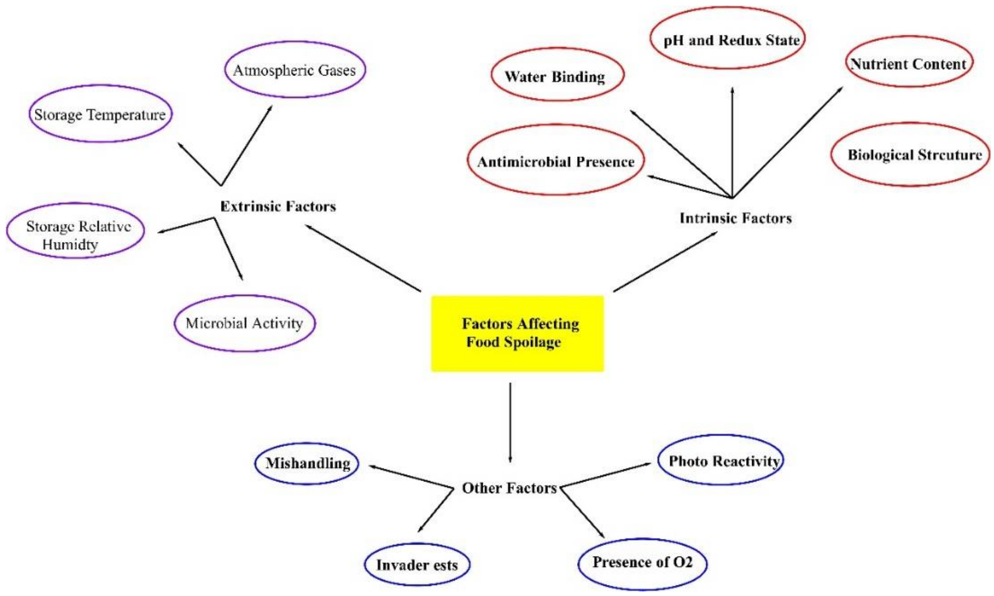

Figure 2. Main factors responsible for food spoilage.

2.2. Types of Electrolyzed Water

Electrolyzed water has been regarded as an emerging sanitizer due to its antimicrobial activity against a wide range of microorganisms within a very short period of time. The production of electrolyzed water (EW) is carried out in an electrolysis chamber, which may contain dilute salt (NaCl) or a solution of hydrogen chloride (HCl) [61]. Electrolyzed water is produced by the electrolysis of dilute salt (NaCl) solution containing a diaphragm to separate the anode and cathode. Depending on the production conditions, the devices being used, and the electrolyte solution, the electrolyzed water can be categorized as alkaline, acidic, or neutral electrolyzed water. Electrolyzed oxidizing water (EOW) with a pH of 2–3, an oxidation-reduction potential (ORP) greater than 1100 mV, and an available chlorine concentration (ACC) of 10–90 ppm is produced at the anode [62]. At the same time, alkaline electrolyzed water, basic electrolyzed water (BEW), or electrolyzed reduced water (ERW) with a pH of 10–13 and an oxidation-reduction potential (ORP) from −800 to −900 is produced at the cathode. Alkaline electrolyzed water (ALEW) with a pH of 10–11.5 and an oxidation reduction potential 800–900 mV is produced at the cathode [63]. Other novel electrolyzed water forms include weak acidic electrolyzed water (WAEW), slightly acidic electrolyzed water (SAEW), and neutral electrolyzed water (NEW). SAEW is produced in a single cell chamber with a pH of between 5.5 and 6.5, an oxidation-reduction potential (ORP) from 800 to 900 mV, and an available chlorine concentration (ACC) between 10 and 80 ppm [64]. SEAW is very popular in China, Japan, and Korea [64–67]. SAEW is produced solely by the electrolysis of HCl or in a single cell unit combined with NaCl [68]. NEW is generated by mixing OH- ions with anodic solutions [69]. The EW is stored in special material containers through conservation in dark conditions or by being converted to other forms, i.e., ice cubes for further use, and the water processing is shown in Figure 1 [70].

The systems for producing this electrolyzed water may be divided into those which may or may not contain a diaphragm to separate the anode and cathode. The machines containing a diaphragm generate acidic electrolyzed water (AEW) and alkaline electrolyzed water (ALEW), while those lacking a diaphragm produce slightly acidic electrolyzed water (SAEW) and neutral electrolyzed water (NEW) [71]. From a food safety perspective, AEW has strong antiseptic effects against food pathogenic microorganisms [71]. However, ALEW, owing to its strong reducing properties, finds its application in removing grease and dust from kitchen utensils, chopping boards, working kitchen surfaces, and others [65]. According to Ramírez Orejel and Cano-Biendía [72], AEW is a promising strategy to preserve different raw meat, ready-to-eat meat, chicken, fish, and others without affecting their sensory characteristics. In this regard, AEW can be applied to different types of food and against different pathogens. Moreover, a variety of products can be candidates for the application of AEW to increase shelf life and decrease the incidence of foodborne diseases [72]. Commercial generators for AEW are of mainly three types, depending upon the automatic controls the systems contain. In the first type, the user can adjust the brine flow rate, while the machine automatically calibrates and adjusts the voltage and amperage. In the second type of generator, the machine accordingly adjusts the brine flow rate while a user can revamp the voltage and amperage. In the third type, the user is allowed to regulate the chlorine concentration level. Thus, depending upon these settings, generators can adjust their voltage, brine flow rate, and amperage [65,71,73]. Various EW-producing systems are summarized in Table 1. The factors determining the physicochemical properties of EW include current values, electrolysis time, water flow during electrolysis, and sodium chloride concentration [74]. Currently, systems for the production of SAEW are developed that provide the basis for the development of domestic and commercial SAEW generators for household and industrial utilization [75]. The purity levels of the water from different purification sources is discussed below in Table 1.

Table 1. pH and concentration of different minerals in water from different sources.

Water	Detected Elements	Ca^{+2} (mg)	Mg^{+2} (mg)	K^{+} (mg)	Na^{+} (mg)
Ordinary tap-water	pH 8.00	24.42	4.98	5.04	46.60
Ultrapure water	pH 8.23	5.32	0.83	0.94	2.88
Acid electrolyzed water	pH 3.00	13.55	2.92	1.71	19.47
SAEW	pH 5–6.5	16.53	3.41	4.96	56.03

Data from Cao et al. [76].

EW has antimicrobial properties against food pathogenic microorganisms attached to cutting boards, kitchen surfaces, poultry and meat carcasses, cell suspensions, and vegetables [73]. The overall antimicrobial activity and action mechanism is not completely understood, and further research is required. Some researchers consider the chlorine present in EW as the major antimicrobial, while others regard ORP as the major factor responsible [73]. Other factors affecting the sanitization efficiency of EW include the water flow rate, current, salt concentration, electrolytes, hardness of the water, water temperature, and electrode material [73].

The effect of ORP, ACC, and pH on the antimicrobial properties of EW is strong, as pH influences the generation of chlorine species. The ORP and ACC of electrolyzed water decline sharply with the upsurge in pH from acidic (2.5) to alkaline (9.0). At pH 9, the antimicrobial efficiency ceased [77]. AEW, owing to its low pH, increases the vulnerability of bacteria towards chlorine in the form of HOCl and thus decreases bacterial growth. Some researchers have proposed that the increased ORP of AEW determines its antimicrobial efficiency [73]. An increasing ORP facilitates the oxidation of sulfhydryl mixtures in the bacterial cell, destroys metabolic pathways, and facilitates bacterial inactivation [73]. Thus, as per principle, a high ORP and low pH facilitate the inactivation of microorganisms.

On the other hand, an increased flow rate of water results in an upsurge in current due to the increased production of salts per unit time [65]. This "acidic electrolyzed water" can have its pH increased by mixing in the desired amount of hydroxide ion solution from the cathode compartment, yielding a solution of hypochlorous acid (HOCl) and sodium hydroxide (NaOH). The varying amperage increase or decrease of the effectiveness of EW is due to its influence on the generation of the chlorine concentration. It has been reported that an increasing amperage improves the sanitizing efficiency of EW, for example, by increasing the current from 1.15 to 1.45 A, a log reduction between 4.9 and 5.6 CFU/mL for *Listeria monocytogenes* and *E. Coli* O157:H7 was found. Moreover, the ORP, ACC, and pH also increased by increasing amperage [78].

The storage conditions also influence the properties of EW. In open conditions, due to the evaporation of chlorine and the breakdown of HOCl, the sanitizing efficiency of EW is diminished [71]. In closed conditions, chlorine losses occur by self-decomposition, but these losses are lower than in open conditions. The ACC of low concentration electrolyzed water diminishes from 10 to 0 mg/L in 7 and 21 days, respectively, under open and closed conditions. However, the pH increases, the ORP decreases, and the bactericidal activity is better sustained in closed storage conditions (14 days). It was reported that the chlorine was lost completely in AEW stored in open conditions after 30-h agitation and 100 h at quiescent storage conditions. However, the lightening does not affect the chlorine retained in EW during storage. As far as the impact of temperature on storage is concerned, the storage of AEW at 4 °C results in a greater stability than at 25 °C.

EW properties and sanitizing efficiency are also affected by the type of electrode, material used, and electrolyte flow rate. It has been reported that the ACC value directly increased with the electrolyte concentration compared to the type of EW, and with an increasing concentration the sanitizing efficiency also positively increased [75]. An increased concentration results in an increased chlorine production, and thus an increased sanitizing efficiency. With an increasing concentration of NaCl, the pH increases and facilitates the production of SAEW within a satisfactory pH range [73]. The choice of electrode material improved the formation of oxidants and reactive species. HOCL, Cl^-, OCl, OH^-, H_2O_2, and O_3 production was also positively influenced by the choice of material used. Moreover, the most significant parameter is the choice of electrode material that affects the production of oxidants [79]. In this regard, Ming et al. [80] studied the effect of electrode material (platinum, iridium, or ruthenium) on the physical and chemical parameters of EW water and concluded that the ruthenium electrode showed the highest value of available chlorine content, while the platinum electrode had the lowest value of available chlorine content.

2.3. Antimicrobial Properties of Electrolyzed Water

The antimicrobial efficacy of EW is affected by the water's temperature and hardness level. In this regard, the microbial efficacy of SAEW improved with the increased temperature of the water [67,81]. The antimicrobial efficacy of AEW was evaluated against *Listeria monocytogenes* and *Salmonella typhimurium* at 4 °C and 25 °C. The results showed the maximum log reduction of more than 8 CFU/mL at 25 °C [82]. On the contrary, other results showed that preheated SAEW presented a greater log reduction against *Listeria monocytogenes* and *E. coli* O157:H7 compared to heated SAEW. The phenomenon has been attributed to the partial loss of ACC while heating [75]. Further research is required to determine the effect of hardness on the properties of EW as limited studies are available. It has been shown that by increasing the hardness level of water, both the free chlorine and the ORP increase, and the decrease in the pH results in the destruction of pathogenic microbes [83]. The increase in water hardness may increase the electrolyte concentration and the electric current or conductivity of the solution and resultantly increase the chlorine production. The factors that affect the properties of EW include voltage, salt concentration, and electrolyte flow rate [83]. It has been concluded that these factors influence the overall attributes of EW, including the sanitizing efficacy. There is a need to develop proper standard operating procedures for the manipulation of EW, and they must be implemented to obtain more benefits from the sanitizing properties of EW.

Compared to other toxic chemical sanitizers, EW has shown significant benefits in the food, agriculture, and pharmaceutical industries, as it is produced in an environmentally friendly manner from distilled water and common salt (NaCl). After usage, it returns to its original form without posing any threat to the environment or consumer [71]. EW is advantageous due to its onsite production. Therefore, it can be produced and used without storage. EW has significant antimicrobial properties against a broad range of bacteria and shows non-selective sanitizing properties. Electrolysis units that are sold for industrial and institutional disinfectant use and for municipal water-treatment are known as chlorine generators. It is also hypothesized that EW does not generate antimicrobial resistance in bacteria. As far as the sensory or organoleptic parameters of food are concerned, these remain unaffected while utilizing acidic electrolyzed water (AEW), neutral electrolyzed water (NEW), slightly acidic electrolyzed water (SAEW), and strongly acidic electrolyzed water (StAEW) [66,71,73,77,78]. Moreover, the cost of EW is negligible compared to its counterparts. The operating cost involves the initial investment of purchasing a generator, along with the water, chemical salts, and electricity expenses [71].

There are a few disadvantages associated with EW, which limit its utilization and applications; hence, attention is required to its possible downsides as well. These downsides include: (i) The chlorine concentration in EW is reduced with time, reducing its bactericidal activity. The reason may be the increased storage time and temperature; therefore, it is suggested that the storage temperature must be low and in closed containers [73]. (ii) The initial investment of the equipment installation and the exhaust system is high, thus limiting the individual applications of EW [71]. (iii) Some generators, when operated below pH 5, release a pungent chlorine odour, which makes it uncomfortable for the operator; therefore, appropriate on-site ventilation is required during operation. (iv) If EW is not supplied continuously with the oxidants Cl_2, HOCl, and H^+ through electrolysis, the EW may start to lose its bactericidal potential at a much faster rate [74]. (v) EW may start losing its antimicrobial activity if it is stored inappropriately or in case of the presence of organic matter in the EW [73]. (vi) While dealing with AEW, corrosiveness, skin irritation on the hands, and phytotoxicity are the major concerns posed due to the high ORP and high free chlorine content [73]. (vii) There is still a need to study ACC after electrolysis, and there no doubt that chlorine is regarded as an active agent of EW. Another obstacle is the generation rate of the EW solutions.

Electrolyzed water is utilized to deactivate pathogenic microorganisms in freshly produced commodities. In 1999, electrolyzed water was used to clean freshly cut vegetables and fruits, particularly carrots, apples, oranges, bell peppers, peaches, spinach, cauliflower, radishes, potatoes, and tomatoes [84]. After thinly slicing the produce and their immersion, rinsing, or immersion/blowing with electrolyzed water (EO) (pH: 6.81, without 20.0 mg/L of Cl), the reduction of bacteria was between 0.5 and 2.8 log CFU/g. The electrolyzed water, constituting almost 50 mg/L Cl, strongly affects bacterial mortality, which is more effective than 15–30 mg/L Cl. This remedy will not cause the off-colouring of freshly produced commodities [85]. The rinsed freshly produced agricultural products are then re-treated with electrolyzed water (50 mg/L). Due to the cumulative effect of the sequential treatment, the use of purified water will not affect the reduction process of the bacteria. When rinsing with ER water (pH: 11.3, electrical conductivity: 870 mV) for 5 min and after a further dip in electrically oxidized water (pH: 2.6, electrical conductivity: 1130 mV, available Cl is 30.0 mg/L) for 5 min, the aerobic mesophilic bacteria are reduced. Compared with soaking in electrically oxidized water (30.0 mg/L available Cl), ozone (5.0 mg/L), or NaOCl solution (150 mg/L available Cl) only, this method of treatment reduces each colony by at least 2 log CFU. Hence, the 10 min in the study of the sequential washing process also provides an inference that lettuce implemented with electrically oxidized water for a time span of 1 min, preceded by water for 1 min, and only acidic EO water for 10 min, reduced aerobic bacteria by 2 log CFU/g; however, after each trial, electrically oxidized water processing did not involve a considerable increment in bacterial reduction [71,86]. According to a scientific study, salad was treated with moderately heated ER water (50 °C) for 5 min, followed by cooling at 4 °C for 5 min. The results inferred that this remedy can cause a reduction in the level of *Salmonella* and *E. coli* O157:H7 by 3.0–4.0 log CFU/g. During the study, freshly cut coriander washed with ozonized water for 5 min, followed by washing with electrically oxidized water (pH—2.45; electrical conductivity—1130 mV; available Cl—15.2 mg/L) for 5 min, effectively reduced the initial count of microbes and slowed down the growth of microbes during storage [87].

Eggshells can be used as a medium for the spread of human pathogens because eggshells may contain *E. coli* O157: H7, *Yersinia enterocolitis*, *Listeria monocytogenes*, and *Salmonella*. Pathogenic bacteria in incubation plants are usually removed by using glutaraldehyde gases, formaldehyde, atomized hydrogen peroxide, or aldehyde. Hence, disinfecting agents can pose a health risk to chickens and human beings [87,88]. Electrically oxidized water (pH—2.2; electrical conductivity—1150 mV; available Cl—8.0 mg/L) while using an electrostatically intensified spray system can thoroughly remove *Salmonella*, *Staphylococcus*, and *Listeria monocytogenes*. A study was conducted under conditions where a 15 s wash time with an electrically oxidized spray to sterilize the animal's stomach inducted with fecal material containing *Listeria*, *Salmonella*, and *Campylobacter* [89]. Recent studies showed that sprinkling with electrically oxidized water (pH—2.4, electrical conductivity—1160 mV, available Cl—50 mg/L) for 15 s could limit the proliferation of *Listeria monocytogenes*, *Salmonella typhimurium*, and *E. coli.* The population capacity was 1.23, 1.67, and 1.81 log on the stainless-steel surface, and it was deduced that a longer contact time could increase the disinfection effect [66,90]. It was reported that in order to sterilize bovine hides before slaughter, electrically oxidized water constituting 70.0 mg/L of available Cl was sprayed sequentially at a temperature of 60 °C. Sprays can reduce the amount of anaerobic bacteria by 3.5 logs CFU/100 cm^2 and the number of *Enterobacter* by 4.3 log CFU/100 cm^2. Recently, soaked or sprayed *Listeria monocytogenes* and hams with electrically oxidized water (pH—2.3; electrical conductivity—1150 mV; available Cl—45 mg/L) and/or ER water. At a storage temperature of 4 °C for 7 days, no significant difference was found between the hunter sausages, Frankfurt sausages, and hams. Electrolyzed water has been used in the medical field for over a century. Before antibiotics were available, electrolyzed water was used to irrigate and disinfect wounds in World War I. The main challenge of using this disinfectant has been keeping it in a stable form for use as a disinfectant. Statistical results have shown that electrically oxidized water has no harmful "whitening" effect on the superficial layer of the instantly tested meat [91,92]. Table 2 shows food the safety applications of different types of electrolyzed water in the food industry.

Table 2. Food safety applications of different types of electrolyzed water.

EW Generating Machine	Salt/Acid Used as Substrate	pH	Reported Food Safety Application	Target Pathogen	Reference
NEW	NaCl (1.0%)	8.6	Lettuce, corn salad, shredded carrots, freshly cut iceberg lettuce	*Salmonella*, *Escherichia coli*	[90]
AEW	NaCl (0.1–0.2%)	2.5	Alfalfa seeds and sprouts, tomatoes	*E. coli* O157:H7, *Listeria monocytogenes*	[93]
NEW	NaCl (25%)	8.27	Plastic and wood cutting boards	*Staphylococcus aureus*, *Listeria monocytogene*, *Pseudomonas*	[94]
SAEW	NaCl (0.1%)	5.9	Pure culture	*Vibrio vulnificus*	[77]
SAEW	HCl (2%)	5.8	Pure culture	*Escherichia coli*, *Salmonella*, *S. aureus*	[83]
SALcEW	NaCl (0.9%)	6.2–6.3	Freshly cut spinach	Total bacteria, yeast, molds, *E. coli* O157:H7, *Listeria monocytogenes*	[73]
SAEW	NaCl (0.6%) and HCl (0.15%)	6–6.5	Pure culture, Lettuce, pork	Total bacteria, *Listeria monocytogenes*	[67,70]

NEW: Neutral electrolyzed water; AEW: Acidic electrolyzed water; SALcEW: Slightly acidic low concentration electrolyzed water; SAEW: Slightly acidic electrolyzed water.

Reports regarding the utilization of electrically oxidized water to inactivate bacterial cells in seafoods revealed that the treatment of raw salmon with electrically oxidized water (pH—2.6; electrically conductivity—1150 mV; available Cl—90.0 mg/L at 35 °C for 64 min, yielded 1.07 log CFU/g) and *E. coli* O157: H7 and *Listeria* reduced 1.12 log CFU/g. Recently, it was pointed out that gloves used for food handling to protect workers and sellers can become carriers of pathogenic bacteria sourced through contact with raw commodities and biologically contaminated food surfaces. Electrolyzing water and CO gas are used to extend the periods of the storage life and the refrigeration time of bluefin tuna (*Thunnus albacares*). It was reported that tuna processed with electrically oxidized water and CO gas constituting 100 mg/L Cl could immediately obtain the lowest level of aerobic plate count (APC) [92]. Totally natural, non-toxic, and completely safe for human use, electrolyzed water is already in use throughout many industries such as healthcare, food safety, and water treatment, as well as for general sanitation purposes. Hypochlorous acid is in fact naturally produced by white blood cells in mammals for healing and protective purposes. The application of electrically oxidized water constituting 50 mg/L or 100 mg/L Cl in tuna steak together with CO gas would be an effective method for improving the quality and freshness of meat and prolonging their refrigeration times. Researchers studied the effects of the electrical conductivity of water on the proliferation of *Fennelella* and *Euglena catenoidea*, and the results proved that the electrically oxidized water is an extremely effective tool for killing toxic algae and destroying toxicity [95].

EO water can be utilized for the disinfection of food processing plants. It was revealed that electrically oxidized water is an efficient method for removing foodborne pathogens from cutting boards. EO water (pH—2.53; electrically conductivity—1178 mV; available Cl—53.0 mg/L) can also cause a reduction in *Enterobacter* and golden grapes on the surface of the glass, steel, glazed plates, stainless steel, non-woven plates, and glass porcelain surfaces. Soaking the culture at different contact places in electrically oxidized water for 5 min under stirring 50 rpm can reduce the population of aerobic *E. coli* and *Staphylococcus* on a test surface to <1.0 CFU/cm^2. *Listeria* is a food-borne and pathogenic bacterium that results in life-endangering listeriosis among high-risk groups [96]. Electrolyzed alkaline ionized water loses its potency fairly quickly, so it cannot be stored for long. Electrolysis machines can be (but are not necessarily) expensive. In some (but not all) instances, the electrolysis process needs to be monitored frequently for the correct potency. Outbreaks of Listeriosis disease are related to targeted foods, with the synthesis of the biofilm *Listeria* at the food processing plant as a significant source of pollution. The *Listeria* oriented biofilms have developed resistance against chlorine, acid anions, and tertiary diammonium sulphate, which are better suited to food processing surfaces and are clean and hygienic. An entire food manufacturing plant was studied against the proliferation of *Listeria* oriented biofilm on the surface of steel and electrically oxidized water and inferred that EO water application for 300 s on the surface of stainless steel could reduce *Listeria monocytogenes* from 1.89 CFU/cm^2 to below the detectable level 5.0 CFU/cm^2.

Moreover, exposure to a 200 mg/L chlorine solution for 300 s can acquire similar results [73]. In the relevant study, the biofilm of *Listeria* on the superficial layer of stainless steel was inactivated with electrically oxidized water. They also inferred that electrically oxidized water does not reduce the biofilm of *Listeria*. Via treatment with electrically oxidized water only, and with chemical purification, each sample reduces the living bacterial count in the biofilm by 4.1–5.3 log CFU (2 $\times$ 5 cm), while the mutual application of ER water and electrically oxidized water can be further reduced by 0.25–1.3 per Log CFU sample of each strain. Stainless steel is the most frequently used biofilm for different contact surfaces of the food industry [70]. It was reported that electrically oxidized water (pH—2.53; electrical conductivity—1077 mV; available Cl—50 mg/L) and chemically altered water (pH—6.12; electrical conductivity—774 mV; available Cl—50 mg/L) had no adverse effects on stainless steel within one week. The different qualities of water and ethylene oxide towards provoking a reduction of bacteria in the pipes of a milking system were studied [97]. Washing with 60 °C ER water for 10 min, and then with 62 °C electrically oxidized water for 10 min, tends to remove all pathogenic bacteria that can be detected on milk-oriented milk surfaces. So, all of these results indicate that electrically oxidized water tends to be used as a cleaning and disinfectant for clean-in-place scenarios (CIP) [81].

Electrically oxidized water is a potential disinfectant and cleaning agent for use by food processing plants in the future. Electrically oxidized water has been approved by US regulatory agencies to replace hazardous chemicals and can be used as an eco-friendly and sustainable remedy for households and industries [98]. Although electrically operated systems have been used in various fields in Ukraine, South Korea, Russia, Finland, Japan, and France for decades, they are gradually gaining popularity in the United States and other technologically advanced countries. Presently, the tendency to continuously grow e-commerce has been observed on a global scale. Electrolysis units that are sold for use as industrial and institutional disinfectants and for municipal water-treatment are known as chlorine generators. Alongside the significance of electrolyzed water, multiple types of industries have been installed to produce ionized water. These industries have asserted the provision of 100% pure, environment-friendly, non-toxic, and low-priced electrically ionized water for commercial, industrial, and domestic use. The EW trademark has been produced by UAE technologies and Empowered Water, an eco-friendly and efficient remedy for CIP industrial usage [99]. Especially in the food industry, CIP and processing applications can wash and sanitize fixed machinery during food processing and system start-up. In different parts of the world, there are differing views on the applications and disinfection regulations of electrolyzed water [100]. Although the field of electro-chemical activation (ECA) technology has existed for more than 40 years, companies producing such solutions have only recently approached the U.S. Environmental Protection Agency (https://en.wikipedia.org/wiki/United_States_Environmental_Protection_Agency (accessed on 1 March 2021)) (EPA) seeking registration. Recently, several companies that manufacture electrolytic devices have sought and received EPA registration as a disinfectant. Due to its advantages, most industries can start using electrolyzed water in the near future. Electrolyzed water has a bright future. Due to its benefits, most food factories will start using electrolyzed water in the next decade [95,101]. Figure 3 shows the microorganisms responsible for food spoilage.

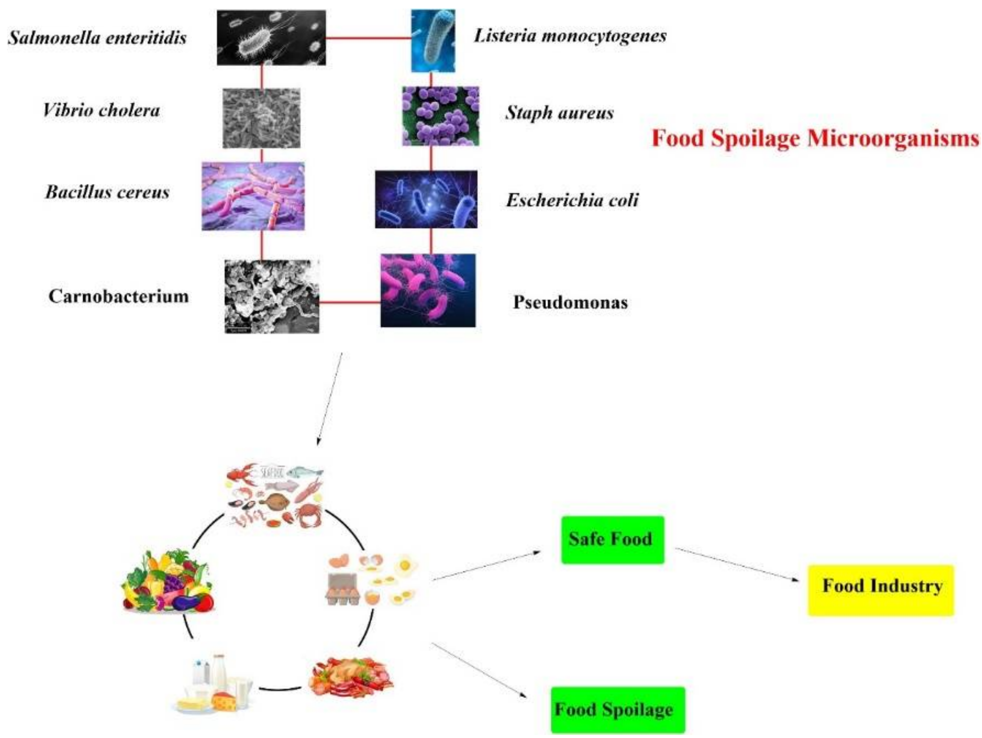

Figure 3. Main microorganisms responsible for food spoilage.

3. Conclusions

EW, an environment-friendly sanitizer, manifests strong antimicrobial properties in various industries, including the food, pharmaceutical, and agricultural industries. Through the development of novel EW such as Strongly Alkaline Electrolyzed Water (StALEW) and Slightly Acidic Electrolyzed Water (SAEW), many of the issues related to corrosiveness that were posed to StAEW and AEW have been resolved. The properties of EW depend on various parameters, such as the temperature of the water, ORP, ACC, electrolyte type, storage conditions, salt concentration, and water flow. The effect of water hardness on sanitizing efficiency needs to be researched further. EW can be utilized in a diverse range of food products and is thereby an appropriate choice for synergistic microbial control in the food industry to ensure food safety and quality without damaging the organoleptic parameters of the food. However, standard operating procedures (SOPs) and proper legislation are needed for direct contact with high porosity foods and equipment surfaces for microbial inactivation. Therefore, through proper research, a dynamic and advanced approach to ensuring sustainable food safety can be developed to overcome all the limitations.

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