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Design and Construction and Energy Consumption Study of a New Electrolyzed Water Cell Generator Prototype for Food Disinfection

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Abstract: This study explores the feasibility of producing electrolyzed water (EW) for post-harvest treatment of fruits and vegetables as a new substitute for current chemical products. A prototype generator using tap water and NaCl solution was tested for EW's sanitization efficiency, energy, and economic costs. In vitro tests on Penicillium e., Aspergillus n., Botrytis c., and Alternaria a. assessed EW pH, chlorine concentration, electro-oxidative potential, pathogen contact time, and energy consumption. Optimal results were achieved with a pH of 4.6, electro-oxidative potential of 188 mV, active chlorine concentration of 3.4 mg/L, and a contact time of 1–2 min. The prototype produced 10.0 L of EW in 1 h, consuming 0.11 kWh of electricity. Real-scale energy consumption was 545 kWh/m^3 EW, costing 12.51 euro/m^3. The study concludes that optimizing EW production can reduce energy consumption, making it a viable alternative for industrial sanitization of fruits and vegetables.

Keywords: anolyte; electrolyzed water; postharvest disease; sanitization

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1. Introduction

Fruits and vegetables constitute most of the human diet; the sanitization of horticultural products plays a significant role in preserving their quality and ensuring consumption safety.

Washing is a critical point in the production process, aimed at removing soil, foreign elements, unwanted product residues, reducing microbial load, and eliminating any presence of chemical contaminants. An industrial washing line typically consists of three tanks connected in series to achieve effective mechanical removal of dirt from product surfaces [1,2]. Relying solely on washing products with running water cannot completely remove naturally occurring pathogenic bacteria [3]. Currently, chemical products such as sodium hypochlorite [4–6] and ozone [7] are used, significantly reducing microbial populations on fresh vegetables [8–11]. However, chlorination systems, while seemingly economically and technologically convenient, have limitations due to the formation of by-products harmful to human health, poor effectiveness against certain microbial species, especially viruses and protozoa [2], and their limited reusability, making it difficult to reduce the energy consumption required for their production. On the other hand, the food industry is known to be one of the most energy intensive [12,13].

Electrolyzed water (EW) generators, used in organic electrolysis systems, have been studied for industrial wastewater treatment, reducing industrial pollution from wastewater disposal [14]. The production of chlorinated compounds from saline water using an electrochemical cell offers numerous advantages over other less sustainable and ecological methods [15,16]. Both goals can potentially be achieved through the electrochemical splitting of saline water, which has demonstrated strong bactericidal activity in inactivating many pathogens [16–20]; moreover, it is an environmentally friendly process where electrons and water are the only reactants [21].

Losses in post-harvest horticultural products due to the presence of pathogens developed during washing are of particular interest in the search for alternative methods that do not cause alterations in the taste or structure of IV Gamma horticultural products [22]. Post-harvest diseases result in significant food waste, as well as problems of food poisoning and acute infections in consumers, with increasing rates in recent decades [23].

Electrolyzed water is mainly composed of hypochlorous acid (HOCl); it is produced by passing an electrical current through a cell immersed in a saturated saline solution of sodium chloride and water. The portion of the solution exiting the anode from the cell has strong oxidizing properties that have shown broad-spectrum inhibitory effectiveness against a wide range of bacteria, viruses, yeasts, and molds [24]. For these reasons, the use of EW has been studied as an alternative to conventional chemical disinfectants in many food productions [25,26] and to mitigate fungal infections in post-harvest [27].

The limited quantity to be used daily could make EW a viable alternative, in terms of energy and economics, for industries requiring high hourly volumes of washing water, reducing the use of chemical products and wastewater treatment costs [18]. The effectiveness of the EW sanitizing solution is determined by the limited contact time and high available chlorine concentration, thus offering treatment flexibility for different products [25]. EW has three main physicochemical properties: acidic pH value, available chlorinated compounds (ACC), and electrochemical oxidation potential (EOP). The variability of these values increases or decreases the sanitizing characteristics of EW, demonstrating interaction effects among these factors [16,23,28].

Chlorine-based chemical solutions have health and environmental limitations: their use leads to the formation of organic compounds suspected of irritating the respiratory tract or being carcinogenic, as well as producing wastewater with a high pollutant load of chemical nature [29–32].

Disinfection with EW is already in use in various hospital sanitation systems [33] and simultaneous production solutions of gaseous hydrogen (H_2) for use in fuel cells are also under study [17]. However, post-harvest treatment of fruit with EW needs further study to achieve results on a larger scale, aimed at industrial transfer. However, there is currently a lack of scientific literature that can demonstrate the actual energy consumption and environmental and economic convenience compared to other systems such as sodium hypochlorite.

This study examines the effectiveness of in vitro treatment on some of the common pathogens present on fruits and vegetables that cause post-harvest diseases and reduce product shelf life. EW was compared with a chlorine-based sanitizing solution commonly used on horticultural products to evaluate the effectiveness of electrolyzed water (EW) as a sanitizing agent for fruits and vegetables, comparing their performance, energy consumption, and economic viability. The research aimed to determine whether EW could serve as an environmentally friendly and efficient alternative for industrial sanitation processes, reducing microbial load and chemical contaminants without altering the taste or structure of the produce.

2. Materials and Methods

2.1. Prototype for Producing Electrolyzed Water (EW)

The EW was produced in a pilot plant (Figure 1), through the electrolysis of tap water and a saturated solution of NaCl.

Figure 1. A prototype of an electrolytic generator used for the treatment of fruits and vegetables with electrolyzed water.

The pilot plant is equipped with the following main components:

- Control panel to manage primary production operations and vary the pH (Figure 2a);
- Connection to the public water supply (Figure 2b);
- Self-cleaning resin filter to remove impurities from tap water (Figure 2c);
- Pressure gauge to manage pressure and, consequently, flow rate (Figure 2c);
- A 100 L tank for NaCl saturated solution (Figure 2c);
- Accumulation tank for electrolyzed water with level sensor (Figure 2d);
- Electrolytic cell with platinum electrodes (Figure 2e);
- One peristaltic pump for feeding tap water (Figure 2e);
- One peristaltic pump for feeding saturated NaCl solution (Figure 2e);
- One peristaltic pump for pH correction (Figure 2e);
- Outlet pipes for anolyte (EW), catholyte and wash water (Figure 2f).

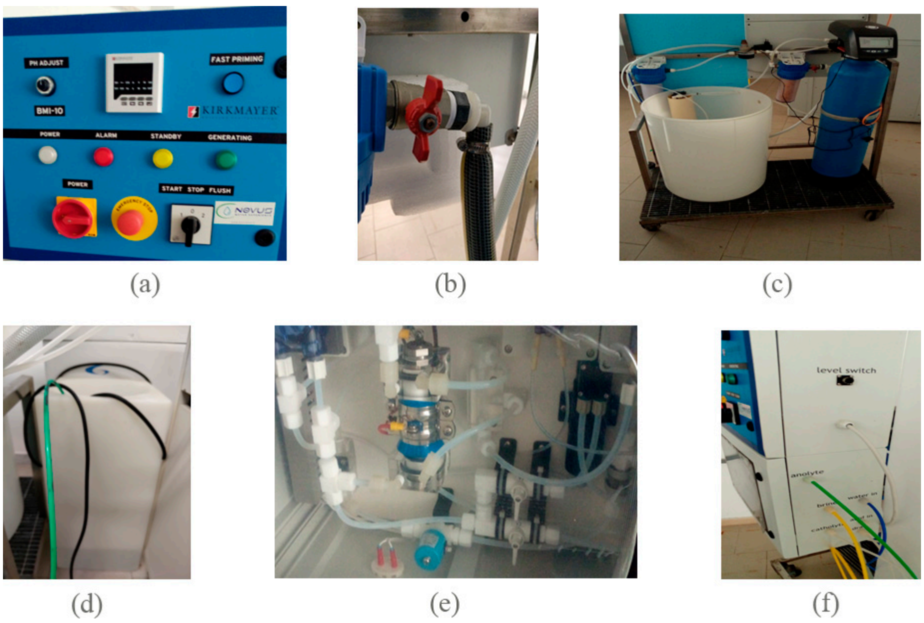


Figure 2. Main components of the designed prototype: (**a**) control panel; (**b**) connection to the public water supply; (**c**) resin filter, brine tank, and pressure gauge; (**d**) storage tank for electrolyzed water; (**e**) electrolytic cell and peristaltic pumps; (**f**) outlet pipes.

The production of EW was carried out at the Laboratory of Machinery and Plants for the Food Industries of the Department of Soil, Plant, and Food Sciences at the University of Bari (Italy) (DiSSPA). The electrolytic cell (internally made of titanium) consists of an anodic electrode (ruthenium–iridium) and a cathodic electrode (titanium) separated by a ceramic septum with a mesh size of 0.2 µm. The electrodes have a total active surface area of 1.5 cm^2, with an electrode thickness of 1.0 mm. The power of the electrolytic cell was varied between 4.0 A and 6.0 A, in relation to the flow pressure of the water/brine solution measured by the pressure gauge positioned downstream of the resin filter and calibrated at 1.0 atm. Its duration is of about two years before recoding. A schematic representation of the process realized by the electrolytic cell is shown in Figure 3.

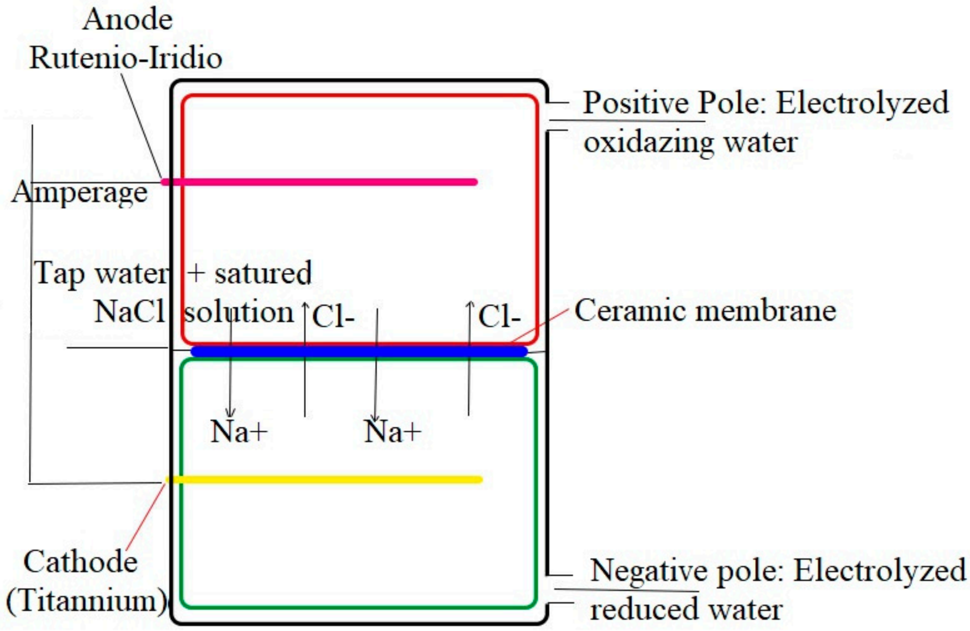


Figure 3. Schematic representation of the electrochemical activation process of saltwater [34].

The electrolysis of tap water and saturated NaCl solution occurs through the dissociation of salt into sodium ions (Na^+) and chloride ions (Cl^-), with the formation of hydroxide ions (OH^-) and hydrogen ions (H^+) in different fractions. The OH^- and Cl^- ions move towards the anode where oxidation occurs with the production of HOCl, ClO^-, HCl, gaseous O_2 and gaseous Cl_2. The Na^+ and H^+ ions travel towards the cathode where they undergo reduction, generating sodium hydroxide (NaOH) and gaseous H_2. Therefore, it is possible to simultaneously produce two types of EW: an acidic solution from the anode (anolyte) and a basic solution from the cathode (catholyte) (Figure 3). Anolyte and catholyte are conveyed into their respective outlet pipes to be collected in different containers. The pH is controlled by management software via a switch located on the control panel; different pH values correspond to different percentages of the catholytic fraction in the electrolyzed water (Figure 2f). The settings of the pH production management software can be modified between 0 and 11.

Since the purpose of the pilot plant is the production of EW for the sanitization of horticultural products, the cell is not currently equipped for the recovery of gaseous hydrogen (Figure 3, [34]). This can be easily achieved with a sealed system for the channeling and storage of H_2 produced at the cathode.

2.2. Experimental Tests

The EW was produced at different pH levels to test the characteristics of the system, setting the water pressure at the inlet to 1.0 atm and the cell power to 5.2 A. Table 1 shows the analytical parameters characterizing the produced water. Free chlorine and total chlorine concentrations (Cl^- mg/L) were determined using the colorimetric method with N,N-diethyl-p-phenylenediamine (DPD), employing a digital chlorine kit (SWAN Chematest 20, Analytic Instrument, Switzerland); pH and EOP were determined using a benchtop pH meter model XS PH60 DHS (GEASS S.r.l., Turin, Italy). Based on the production conditions, three categories of EW were obtained: AEW, SAEW, and BEW (Table 1).

Table 1. Analytical parameters of the EW used in the tests.

Type of EW	pH	EOP (mV)	ACC (mg/L)
Acid Electrolyzed Water	3.8/4.0	>200	20–60
Soft Acid Electrolyzed Water	5–5.8	200	10–30
Basic Electrolyzed Water	8.7/9.2	>−100	80–100

A high flow rate of water/brine at the inlet results in a shorter electrode action time on the solution, decreasing the EOP, chlorinated, and oxidizing compounds. The test was conducted at room temperature, while industrial cells operate at 60 °C [16]; a higher temperature increases ionic conductivity and, consequently, the active characteristics of the EW.

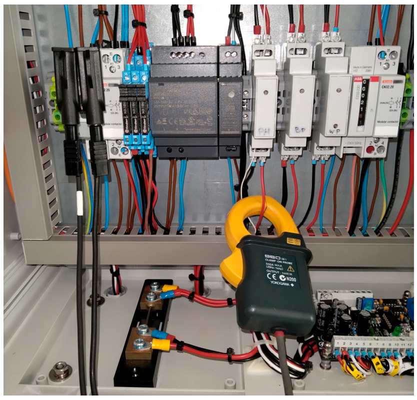
The EW was produced by operating the cell for 20 min; for each pH value, analytical characteristics were determined at various dilutions from 1% to 10% and 100%: electrochemical oxidation potential (EOP), pH, and free and bound chlorinated substances. The EW was tested in vitro on some of the pathogens commonly found on fruits and vegetables during post-harvest treatment that cause diseases and rot: Penicillium, Aspergillus, Alternaria and Botrytis. Pathogenic conidia were collected from colonies grown for 3–4 days at 26/27 °C on Potato Dextrose Agar (PDA).

To prepare the initial solution, each plate was washed with 10.0 mL of 0.1% Tween 20 (Sigma-Aldrich, Milan, Italy) and the conidia were collected from the growth plate by gently scraping the surface with a sterile spatula.

For each pathogenic agent on which determinations were made, three replicates were performed, and the experiment was repeated twice. After the conidia grew on the plate with the sanitizing solution and the control test with distilled water, on the fourth day of incubation at 26 ± 1 °C, the Ufc colonies were counted.

Once the optimal production parameters were obtained, a mass balance was performed for the input and output. The mass balance was carried out by measuring the volume of tap water input, the volume of saturated NaCl solution, and the volumes of the anolyte and catholyte fractions' output for the different operating modes. The energy balance was performed by measuring the active electrical power absorbed by the prototype during production. An energy meter with a data logging function, from Yokogawa company, model CW121, was used for this purpose; this instrument allows measuring the energy consumption of single-phase and three-phase loads, considering the possible load imbalance on each phase. The measurements were taken by inserting the instrument's current probes into the electrical line between the electrical panel and, respectively, the general power supply of the machine, the electrolytic cell, the feed pump of the cell, the feed pump of the saturated solution, and the discharge pump of the catholyte (Figure 4).

The results of the mass and energy balances were used to evaluate the production of EW with the required characteristics, comparing the energy costs related to the industrial production of sodium hypochlorite [35,36], currently proposed in appropriate formulations in industrial sanitation systems. Economic evaluations were made based on the specific energy costs to produce EW and 14% sodium hypochlorite, considering the current costs on the national electricity market [37].



(a) (b)

Figure 4. (**a**) Instrument for measuring energy parameters; (**b**) electrical panel of the machine.

3. Results and Discussion

Setting the pH value to 1 on the control panel of the pilot plant yields electrolyzed water with actual pH values ranging from 4.1 to 5.2, obtained with 90% and 99% distilled water, respectively, and pH 3.38 obtained with 100% EW (Table 2); consequently, the EOP values decrease from 172 mV to 94.8 mV and DPD from 2.33 mg/L to 1.87 mg/L (Table 2). A similar effect is obtained by setting the pH value to 10 on the control panel: the electrolyzed water has actual basic pH values ranging from 7.8 to 7.5, respectively, obtained with 90% and 99% distilled water and pH 8.20 at 100% EW (Table 3); the corresponding EOP values vary from −49.5 mV to −43.5 mV, while DPD varies from 7.4 mg/L to 1.1 mg/L (Table 3). In the production of electrolyzed water, setting the pH to 5 on the control panel, on the other hand, results in substantially comparable values of pH, EOP, and DPD (Table 4).

Table 2. EW production at pH = 1 set on the control panel.

Parameters	Dilution Rate Electrolyzed Water									
	1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**10%**	**100%**
pH	5.20	5.02	5.21	4.64	4.60	4.38	4.24	4.23	4.10	3.38
DPD (mg/L)	1.87	1.41	1.13	2.38	1.74	2.29	2.02	1.91	2.33	
Total chlorine (mg/L)	2.20	1.69	1.32	2.48	1.95	2.31	2.07	1.95	2.34	
Bound chlorine (mg/L)	0.33	0.28	0.19	0.10	0.21	0.02	0.05	0.04	0.01	
EOP (mV)	94.8	115.8	126.8	139.0	145.8	155.7	157.9	166.5	172.0	217.0

Table 3. EW production at pH = 10 set on the control panel.

Parameters	Dilution Rate Electrolyzed Water									
	1%	**2%**	**3%**	**4%**	**5%**	**6%**	**7%**	**8%**	**10%**	**100%**
pH	7.50	7.72	7.70	7.65	7.70	7.80	7.80	7.90	7.90	8.20
DPD (mg/L)	1.10	1.46	2.13	3.14	3.81	3.86	4.90	5.70	7.40	
Total chlorine (mg/L)	1.10	1.56	2.21	3.15	3.91	3.97	5.30	5.80	7.60	
Bound chlorine (mg/L)	0.00	0.10	0.08	0.01	0.10	0.11	0.40	0.10	0.20	
EOP (mV)	−43.5	−42.3	−41.2	−42.7	−41.3	−41.7	−51.3	−47.0	−49.5	−60.1

Therefore, it appears that, under extreme operating conditions of the machine, the actual pH and electro-oxidative properties of the produced EW are influenced by the characteristics of the tap water, as different values were obtained from those set on the control panel. The same parameters are also influenced by the percentage of distilled water used in the dilution phases. Conversely, no variations in actual pH and electro-oxidative capacity are observed in the respective dilutions with distilled water from 90% to 99% when an intermediate value is set on the control panel of the machine, highlighting that production parameters are not particularly influenced by tap water and the level of dilution with distilled water in this case.

Table 4. EW production at pH = 5 set on the control panel.

Parameters	Dilution Rate Electrolyzed Water									
	1%	2%	3%	4%	5%	6%	7%	8%	10%	100%
pH	4.60	4.40	4.45	4.20	4.50	4.56	4.65	4.46	4.55	5.11
DPD (mg/L)	1.60	2.00	2.10	2.50	2.80	3.40	4.10	4.90	8.00	
Total chlorine (mg/L)	1.80	2.10	2.40	2.70	3.00	3.70	4.30	5.00	8.00	
Bound chlorine (mg/L)	0.20	0.10	0.30	0.30	0.20	0.30	0.20	0.10	0.00	
EOP (mV)	186.0	187.0	187.0	189.0	190.0	188.0	188.0	193.0	193.9	205.0

Therefore, in the industrial production of EW, plants must provide suitable control systems and standardization of parameters of the incoming tap water to ensure the exact correspondence of the set parameters with the actual parameters of the produced electrolyzed water, avoiding the need for subsequent analyses.

Figures 5–7 refer to the best results obtained in the inhibition tests performed, which are related to the contact times and the volume of EW used, considering the industrial needs in the sanitization of fruit and vegetable products. These can be summarized as follows: inhibition of pathogens ranging from 85% to 90% compared to the initial value, reduced contact times with the sanitizing solution and minimal volumes of EW to be used in the sanitizing solution.

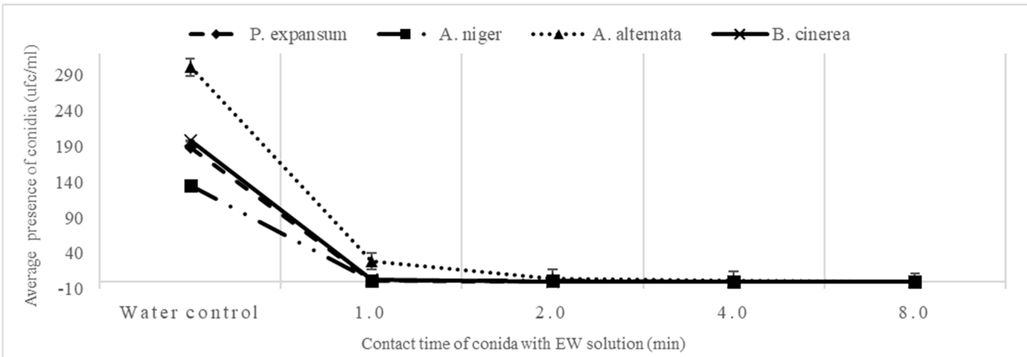


Figure 5. Inhibition curves of the four pathogens as a function of contact time with 6% EW solution and pH 4.56 (see Table 4—6th column).

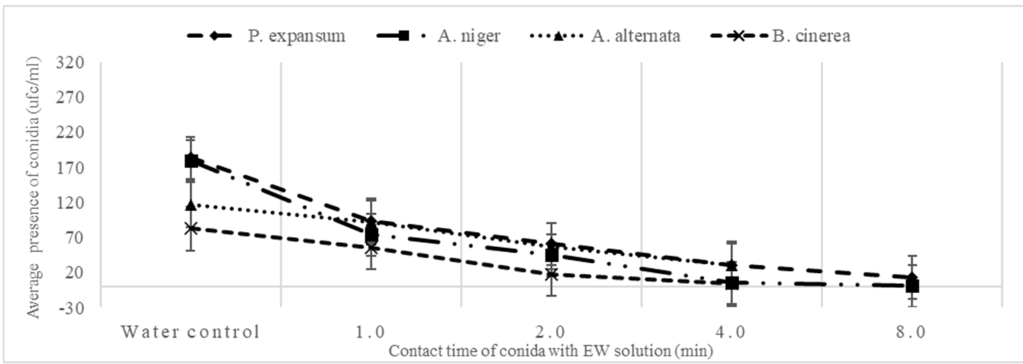


Figure 6. Inhibition curves of the four pathogens as a function of contact time with 6% EW solution and pH 7.80 (see Table 3—6th column).

Compared to the control, consisting of a pathogen solution and distilled water, EW diluted with 94% distilled water, pH 4.56, EOP 188 mV, and DPD 3.40 mg/L (Table 4, column 6) allows, just after 1.0 min of contact, for the achievement of effective sanitization, with a reduction of the initial pathogen load never less than 90%; after 2.0 min of contact, the level of sanitization is 100% (Figure 5). EW diluted with 94% distilled water, pH 7.80, EOP −41.7 mV, and DPD 3.86 mg/L (Table 3, column 6) provides less effective sanitization results: reduction of the initial pathogen load by 80% after 4.0 min of contact and reduction of 90% after 8.0 min of contact (Figure 6). EW diluted with 94% distilled water, pH 4.38, EOP 155.7 mV, and DPD 2.29 mg/L (Table 2, column 6) provides intermediate sanitization results: reduction of the initial pathogen load by 90% for Penicillium e., Aspergillus n., Botrytis c., and 74% for Alternaria a. after 1.0 min of contact, reduction of 100% after 2.0 min of contact for Penicillium e., Aspergillus n., Botrytis c., and 4.0 min for Alternaria a. (Figure 7).

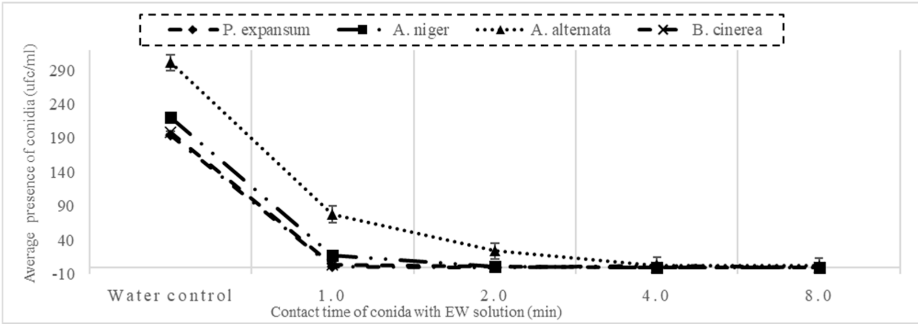


Figure 7. Inhibition curves of the four pathogens as a function of contact time with 6% EW solution and pH 4.38 (see Table 2—6th column).

Therefore, the results obtained with EW at pH 4.56 are comparable to those obtained with EW at pH 4.38 for Penicillium e., Aspergillus n., and Botrytis c., but are better for Alternaria a.

The results may be due to the acidic pH, which caused a greater sensitivity of the cellular membranes of the pathogenic conidia, altering their physiology, hindering replication, and allowing the penetration of acidic compounds [38]. Additionally, a high EOP influenced the production of metabolic compounds such as ATP; the oxidizing compounds likely damaged the cellular lipid membranes, denatured proteins, hindered their reproduction and destroyed bacteria by cutting DNA, thereby inhibiting enzymatic activity [38,39].

Therefore, it is possible to propose the production of EW on a real scale with a maximum dilution of 94%, pH 4.56, EOP 188 mV, and DPD 3.4 mg/L; this could meet industrial sanitization needs for fresh fruit and vegetable productions and ensure continuity in washing lines, thanks to contact times of less than 2 min. This type of EW yielded comparable results to those obtained using a 14% sodium hypochlorite sanitizing solution, with a 97% dilution; in laboratory tests, this solution proved to be the most effective against the studied pathogens (Figure 8) and is one of the most used sanitizing solution formulations in the industrial fruit and vegetable sector.

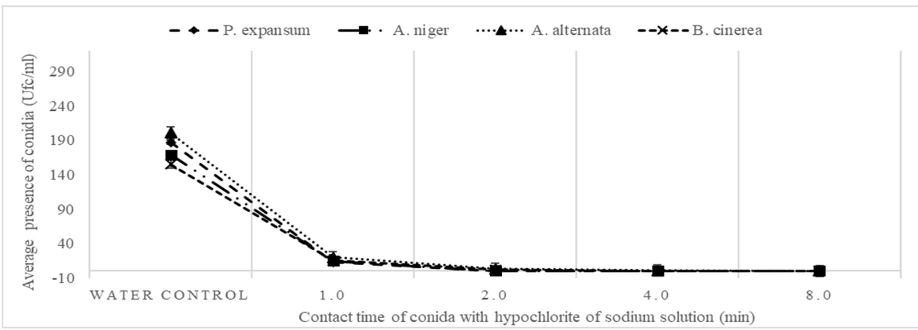


Figure 8. Inhibition curves of the four pathogens as a function of contact time with 6% EW solution and pH 4.56 (see Table 2—6th column).

Table 5 presents the mass balance related to the production of different types of 100% EW, setting various pH values on the control panel of the prototype. In all cases, a production rate of 10 L/h was assumed.

Table 5. Mass balance related to the production of different types of EW with different pH values on the prototype control panel.

pH	Flow Rate (L/h)	Brine (L)	Main Water (L)	Anolyte Produced: EW (L)	Catholyte as Difference (L)
1	10	0.18	9.82	6.6	3.4
3	10	0.18	9.82	6.6	3.4
5	10	0.11	9.89	7.5	2.5
7	10	0.11	9.89	7.5	2.5
10	10	0.10	9.90	9.9	0.1

It appears that to produce 10 L/h of EW, decreasing volumes of saturated NaCl solution must be used depending on the level of basicity of the obtained EW; the values range from 0.18 L corresponding to the highest acidity levels to 0.10 L corresponding to the maximum basicity level. Indeed, to produce more acidic water, a greater quantity of chlorine is required for the formation of hydrochloric acids; consequently, the consumption of tap water tends to increase depending on the production pH (Table 5). Additionally, it is noted that decreasing acidity results in a larger quantity of EW (anolite) as a greater volume of catolite is needed to reach the set basicity; thus, the fraction of waste catolite is reduced (Table 5). The possibility of containing waste volumes is significant when considering that, based on the obtained results (Figure 5), an amount of EW equal to 60–80 L per cubic meter of sanitizing solution can be expected, despite there being no current industrial applications of EW in fruit and vegetable processing plants.

In the pilot plant used, the active power absorption during the production of EW is attributed to the electrolytic cell and the three peristaltic pumps: one for feeding tap water, one for feeding the saturated NaCl solution, and one for pH adjustment by appropriately mixing the discharge of catolite into the anolite exiting the cell. The trend over time of the machine's active power is relatively constant (Figure 9); the tap water feeding pump averages 4.4 W (Figure 10, Table 6). Following are the pumps for pH adjustment and feeding the saturated solution, with average absorptions of 6.6 W and 2.4 W, respectively (Figures 11 and 12, Table 6). The electrolytic cell has the highest absorption, with an average value of 54.5 W (Figure 13, Table 6).

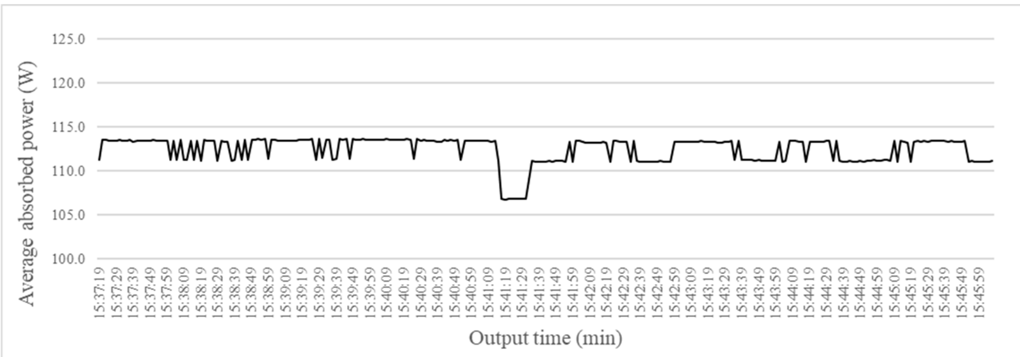


Figure 9. Global active electrical power absorption of the prototype EW generator, as a function of time.

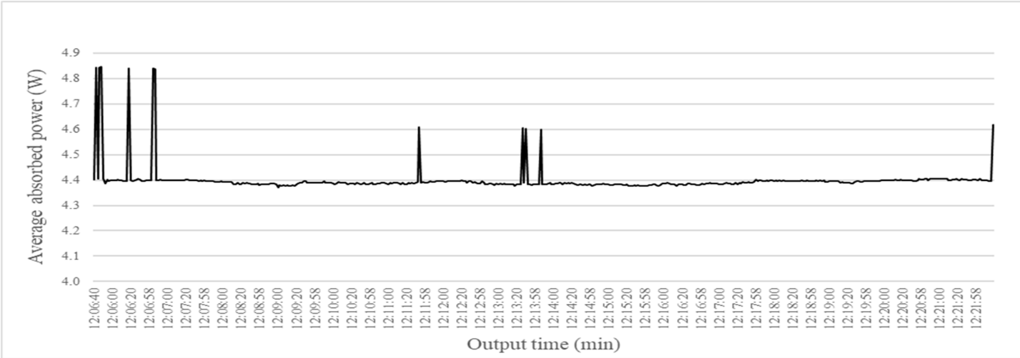


Figure 10. Active electrical power absorption of the main water pump.

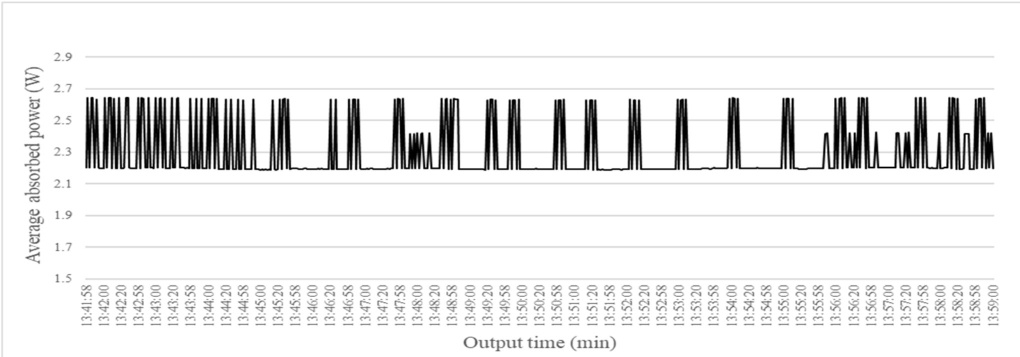


Figure 11. Power consumption of the pump for the saturated solution.

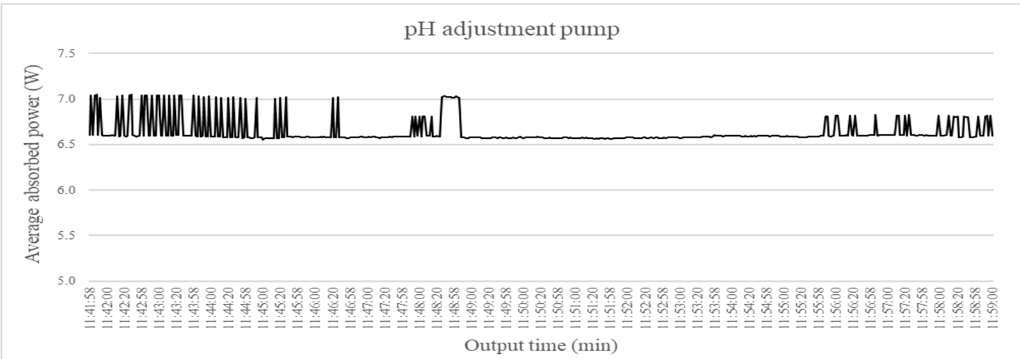


Figure 12. The power consumption of the pH adjustment pump.

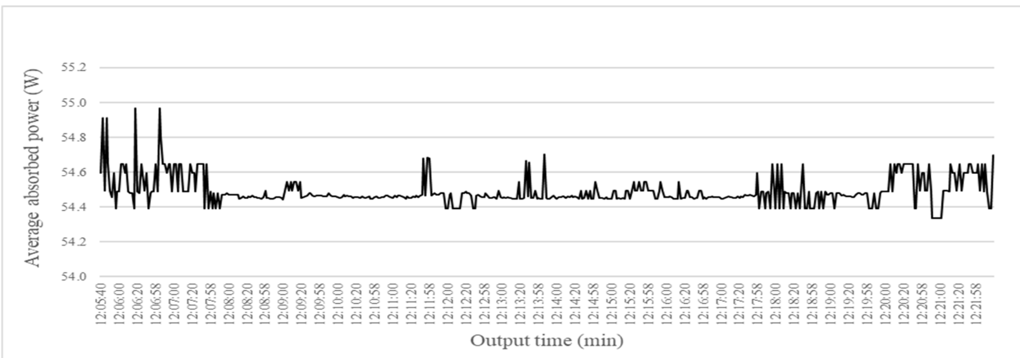


Figure 13. The active electrical power absorption of the electrolytic cell.

Table 6. Average energy parameters, distinguished for the individual components of the machine, relating to the production of 10.0 L/h of EW.

Machine Components	Electrolyzed Water Generator	Electrolytic Cell	Feed Water Pump	Saturated Solution Feed Pump	pH Adjustment Pump
Process duration	60 min	60 min	60 min	60 min	60 min
Active power (avg)	109.6 W	54.5 W	4.4 W	2.3 W	6.6 W
Active power (std)	1.08858	0.08303	0.05607	0.17923	0.13308
Specific active power	0.1 kW/L	0.05 kW/L	0.004 kW/L	0.002 kW/L	0.006 kW/L
Energy	0.01 kWh/L	0.05 kWh	0.004 kWh	0.002 kWh	0.006 kWh
Specific energy	0.001 kWh/m^{3}EW	0.005 kWh/m^{3}EW	0.00004 kWh/m^{3}EW	0.00002 kWh/m^{3}EW	0.00006 kWh/m^{3}EW

The peaks in machine absorption can be attributed to the stabilization of the set pH value through appropriate interventions by the saturated solution feeding pump and the pH correction pump. Indeed, the tap water feeding pump has a substantially constant consumption due to its continuous operation (Figure 10); however, the saturated solution pump (Figure 11) and the pump for mixing catolite with anolite operate in a pulsative manner to maintain the set pH value through appropriate mixing (Figure 12). The absorption peaks characterizing these latter two pumps are around 0.2–0.4 W; for the saturated solution pump, these peaks are due to the supply of the cell with a solution flow suitable for obtaining anolite with the set pH value, increasing the flow rate in cases where the set value is more acidic. Similarly, the pH adjustment pump operates downstream of the cell with appropriate mixing of catolite into EW, varying the flow rate increasingly according to the basicity it must achieve, always based on the set values.

Except for the startup phase of the plant, the active power absorption of the electrolytic cell does not vary over time, with slight variations not exceeding 0.2 W (Figure 13).

Using the prototype developed, the production of 10.0 L of EW was carried out in 1.0 h (Table 6), with an average active power absorption of 109.6 W, corresponding to an electricity consumption of 0.11 kWh and a specific energy of 0.001 kWh/LEW (Table 6). Therefore, considering the substantial linearity, the measured data can be extrapolated to the production of 1.0 m^3 of EW with the best sanitization characteristics (Table 4): a power commitment of 110.0 W, a total energy consumption of 11.0 kWh, a specific power commitment of 11.0 kW/m^{3}EW, and a specific consumption of 0.01 kWh/LEW (Table 7).

Table 7. Energy parameters related to the production of: EW, industrial $NaClO_2$, and $NaClO_2$ at 14%.

	Average Active Power	Work Time	Electrical Energy Absorbed	Specific Electrical Energy
EW Generator 1.0 m^3/h	545 kWh/m^3	1 h	545 kWh	0.545 kWh/L
ECA $NaClO_2$	1740 kWh/m^3	1 h	1740 kWh	1.74 kWh/L
$NaClO_2$ 14%	244 kWh/m^3	1 h	244 kWh	0.244 kWh/L

In terms of energy, the industrial production of 14–15% sodium hypochlorite in a conventional industrial system involves the electrolysis of a saline solution and the direct production of Cl_2 and H_2 gases, as well as NaOH in aqueous solution, through chlor-alkali electrolysis (ECA). A typical ECA process involves an energy consumption of 2.1–3.0 MWh per 1.0 ton of production [35,36]; to produce 1.0 ton of Cl_2, the energy cost corresponds to 51–58% of the production energy cost (Table 7), which, calculated with the maximum values, results in: 1.74 MWh (Table 7).

For the industrial sanitization of fruits and vegetables, a 14% aqueous solution of $NaClO_2$ is used, with an energy cost corresponding to 244 kWh/m^3 (Table 7), while the energy cost of the sanitizing solution EW at pH 4.56 is higher: 545 kWh/m^3 (Table 7). This energy comparison apparently finds confirmation in the economic one: 12.51 c€/m^3 to produce EW and 5.60 euro/m^3 to produce 14% $NaClO_2$ (Table 8). However, in the overall balance, it should be considered that industrial sodium hypochlorite production is highly energy-intensive and has a high environmental impact, as it uses mercury electrolytic cells and produces toxic purification sludge [35,36]; furthermore, the use of a Sodium Hypochlorite-based solution in a fruit and vegetable processing plant is limited to a few steps in the washing tanks. On the contrary, the EW system operates discontinuously, in which 1.0 m^3 of EW would be sufficient to ensure industrial sanitization for several days of fruit and vegetable production, thus reducing daily energy consumption to values lower than those of $NaClO_2$. In fact, the washing water that uses EW can be filtered, removing suspended solid residue, and reused again, possibly only requiring minimal integrations to restore initial sanitization values.

Table 8. Energy and economic parameters relating to the dilution in a sanitizing solution of 1.0 m^3.

	Energy Cost	**Gross Price c€/kWh 22.97**	**Cost 6% Ew Solution**	**Cost 3% Sodium Hypochlorite 14% Solution**
EW generator	545 kWh/m^3EW	12.51 €/m^3EW	0.07 c€ *	
ECA $NaClO_2$	1740 kWh/m^3 $NaClO_2$	39.97 €/m^3 $NaClO_2$		
$NAClO_2$ 14%	244 kWh/m^3 $NaClO_2$	5.60 €/m^3 $NaClO_2$		0.02 c€ *

4. Conclusions

EW demonstrated strong bactericidal activity, effectively inhibiting common post-harvest pathogens such as Penicillium, Aspergillus, Alternaria, and Botrytis. With a pH of 4.56, an electrochemical oxidation potential (EOP) of 188 mV, and 3.40 mg/L of free chlorine, EW achieved 90% pathogen reduction within 1 min and 100% within 2 min, showing comparable or superior efficacy to a 14% sodium hypochlorite solution and making it a viable alternative for sanitizing fresh produce. The production of EW was found to be less energy-intensive compared to the industrial production of sodium hypochlorite, particularly with the discontinuous operation of EW systems in industrial settings. The specific energy consumption for EW production was 0.01 kWh/L while the cost of producing EW was higher (12.51 euro/m^3) compared to sodium hypochlorite (5.60 euro/m^3). The higher cost is offset by the potential for reusing washing water and the reduced environmental impact. EW production systems are more sustainable, with fewer by-products and reduced pollution compared to traditional chlorination methods. Additionally, EW systems offer flexibility in sanitization processes due to their quick action and ability to be integrated into existing washing lines. The pilot plant results suggest that industrial-scale EW production could meet sanitization needs efficiently, with lower environmental and health impacts. In conclusion, EW is a promising alternative to conventional chemical disinfectants in the food industry, particularly for the post-harvest treatment of fruits and vegetables. Its effectiveness, coupled with environmental and potential long-term economic benefits, supports further development and adoption in industrial applications. The results of this study also provide useful insights for the design of machines for EW production, concerning energy usage, control systems, and operating parameters of the electrolytic cell and pumps.

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