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Sanitization Treatment of Fresh Produce with Acidic Electrolyzed Water: Experimental Results on Energy Efficiency, Effectiveness on Rots, Cost and Environmental Impact at Near-Industrial Scale

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Abstract: This study evaluates the potential of acidic electrolyzed water (AEW) as an alternative sanitizing solution for the fruit and vegetable industry. Conducted on a near-industrial scale, the experiment used a 300 L solution with 10% AEW, measuring pH, free chlorine concentration, and electro-oxidative potential (EOP). The sanitizing efficacy of AEW was tested against common phytopathogens responsible for post-harvest decay including *Penicillium expansum*, *Aspergillus niger*, *Botrytis cinerea*, and *Alternaria alternata*. With a pH of 7.27, EOP of −0.40 mV, and free chlorine at 5 mg/L, AEW achieved an 85–90% decay reduction in a 2 min wash. Energy consumption for AEW production was notably lower than that for sodium hypochlorite, a widely used industrial sanitizer, and AEW production demonstrated a reduced environmental impact due to its recycling potential and favorable effluent properties. However, free chlorine levels necessitated further treatment before wastewater discharge.

Keywords: acidic electrolyzed water (AEW); fresh produce sanitization; energy efficiency; post-harvest decay; environmental impact; mass and energy balance

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1. Introduction

Post-harvest washing is the first critical control point (CCP) in the processing chain, aimed at removing soil and debris, reducing epiphytic microbial load, and eliminating chemical contaminants that may have been used during cultivation [1,2]. An industrial washing line typically consists of a series of tanks; however, washing with only running water does not guarantee the complete removal of naturally occurring pathogenic microorganisms [3]. Therefore, chemicals such as sodium hypochlorite, acetic acid [4–6], and ozone [7] are currently used to reduce microbial populations to food safe levels [8–11]. Nevertheless, chlorination systems, although economically favorable compared to other methods, have notable drawbacks, including the formation of harmful substances, both volatile and in solution, which pose health risks and lack efficacy against certain microbial species, especially viruses and protozoa [2].

There is ongoing research to develop sanitization methods that do not alter the taste or texture of fresh produce [12], as post-harvest organoleptic alterations lead to significant food loss and an increased incidence of food-borne illness, with cases rising over recent decades [13–15]. Table 1 highlights some of the sanitization systems studied for the treatment of fruits and vegetables under laboratory conditions.

Table 1. Main substances used for the control of post-harvest pathogens of fruits and vegetables [14].

Substance	Treatment Time	Concentration	Pathogen
Chlorine (hypochlorite)	88.4 s	200 mg L $^{-1}$ di cloro libero	*P. digitatum*
Chlorine dioxide	5 min	3.0 o 5.0 mg L^{-1}	*B. cinerea*
Ozone	1 h	11.410 µL L^{-1}	*B. cinerea*
Hydrogen peroxide	Dive for 10–90 s	5–15%	*P. digitatum*
Acetic acid	30 min	1.9–2.5 µL L^{-1}	*P. expansum*
Oxalic acid	10 min	5 mM	*C. gloeosporioides*
Citric acid	30 min	600 g/L	*B. cinerea*, *P. expansum*, and *A. niger*

Acidic electrolyzed water (AEW) possesses three key physicochemical properties relevant to sanitization: acidic pH, free chlorinated compound content, and electro-oxidative potential (EOP). The interaction of these properties has shown synergistic effects that enhance or diminish sanitization characteristics [16–20]; for these reasons, AEW is already in use in various sanitization systems [21–23]. The limited daily usage requirement makes AEW a viable alternative, both energetically and economically, for industries that demand large volumes of washing water. This solution reduces the need for chemical products and the subsequent wastewater treatment costs prior to discharge into public sewage systems [16,24–27]. Electrolyzed water generators are organic electrolysis systems, developed over many years, primarily for industrial wastewater treatment [17]. In terms of sustainability and environmental protection, electrolyzed water (EW) production using electrochemical cells offers numerous advantages over other sanitization methods [13,27]. AEW has demonstrated a strong ability to inactivate many pathogens on fruits and vegetables [26–28]. It is also a low-impact process, where electrons and water are the only reactants [29]. In a recent laboratory-scale study [17], AEW was produced using a specific prototype, and in vitro tests were conducted. The results showed that by setting a pH of 5 on the prototype's control panel and using a 6% dilution in distilled water, the inhibition factors of phytopathogenic microorganisms reached up to 95%, compared to the control with distilled water alone [30,31]. The effluent from the anode of the electrolytic cell (AEW) exhibits strong oxidizing properties, with demonstrated inhibitory effects against a broad spectrum of viruses, yeasts, and filamentous fungi [16,32,33]. Consequently, there is a scientific basis for using AEW in the food sector as an alternative to the current chemical disinfectants [26,27,34], particularly for mitigating fungal infections in the post-harvest phase [27,29,35]. Regarding wastewater generated by this type of production, a previous study [17] found that the acidic sanitizing water had a pH lower than generally permitted under wastewater discharge legislation [36]. However, it is worth noting that the tests in that study used distilled water; under real conditions, tap or groundwater might offer a more effective buffering capacity due to their salt content.

In the present study, near-industrial scale experimental trials were conducted using AEW on fresh produce to assess the treatment's efficacy against pathogens responsible for fruit decay during storage. Controlling these pathogens contributes to reducing food waste. The small-scale trials also aimed to establish design criteria for specific machines for AEW production, as well as to gather data on energy, functional, economic, and environmental performance approaching real-scale conditions. Additionally, the study provided a basis for comparison with chlorine-based industrial sanitizers commonly used in the post-harvest processing chain.

2. Materials and Methods

The experimental tests were conducted at the laboratories of NOVUS s.r.l. (Via Enrico Fermi 18, Brindisi, Italy) on fresh fruit and vegetable products: beetroot leaves, cherry tomatoes, Golden Delicious apples, and chicory leaves. The choice of products was motivated by the fact that they were seasonal fruit and vegetables during the period in which the test was carried out: furthermore, in industrial production, these fruit and vegetables, after washing, do not undergo further sanitization processes either at retail or for the subsequent production of the IV range.

2.1. Generator for Electrolyzed Water (EW) Production

AEW was produced using an electrolyzed water generator (Figure 1) through the electrolysis of groundwater and a saturated industrial-grade sodium chloride (NaCl) solution (Chimpex Industriale S.p.A., Via Valtorta 48, Milan, Italy). AEW production was carried out with a generator prototype previously used to conduct in vitro tests on various phytopathogens in a recent experiment [17].

Figure 1. Generator used for AEW production.

Based on previously obtained results, technical adjustments were made to the current system to enhance functionality while maintaining the physicochemical characteristics (pH, EOP, free chlorine) of AEW, which showed the highest inhibitory activity in laboratory-scale tests (Table 2) [17].

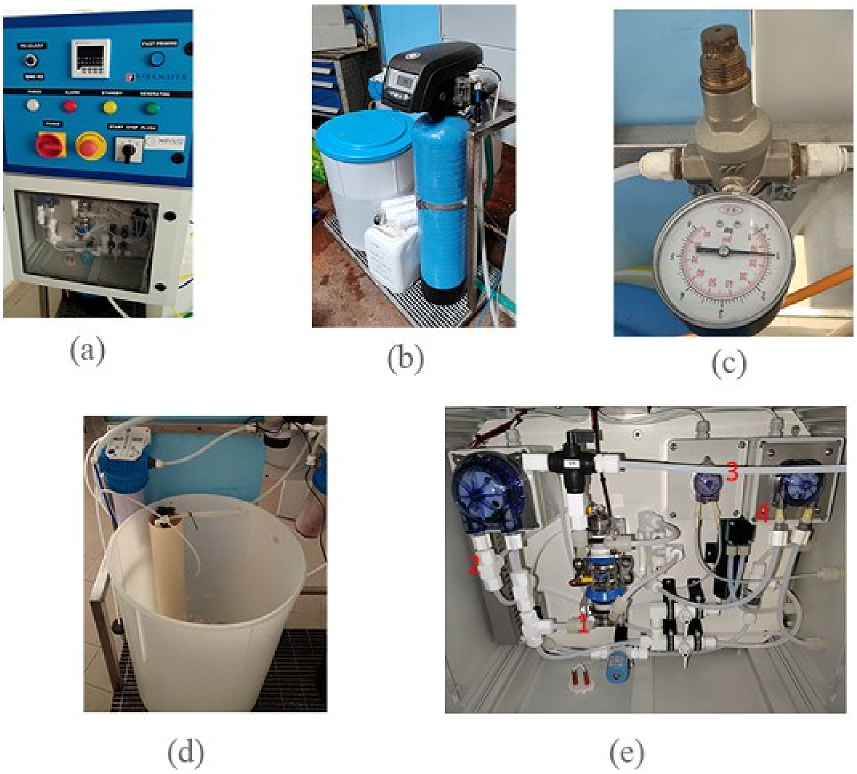
Table 2. AEW production at pH = 5 set on the control panel at production volume of 10 L/h.

Parameters	**Dilution Rate of Acid Electrolyzed Water**				
	6%	**7%**	**8%**	**10%**	**100%**
pH	4.56	4.65	4.46	4.55	5.11
Free chlorine (mg/L)	3.40	4.10	4.90	8.00	>8.00
EOP (mV)	188.0	188.0	193.0	193.9	205.0

Therefore, the AEW produced by the electrolytic cell at 100% (Table 2, column 5) was diluted to 10% with well water to obtain the sanitizing solution used in the experimental trials of the present study. The following analytical parameters were determined for well water and the sanitizing solution: pH, ORP, and free chlorine.

For the small-scale production trial, the AEW generator was assembled with the following components (Figure 2):

- Control panel to manage AEW production (Figure 2a).
- Self-cleaning resin filter to remove impurities from the groundwater (Figure 2b).
- Pressure gauge and manual valve to regulate the pressure and flow rate of water exiting the filter (Figure 2c).
- A 100 L tank for the saturated NaCl solution (Figure 2d).
- Electrolytic cell with electrodes (anode made of ruthenium-iridium and cathode made of titanium) (Figure 2e—1).
- Peristaltic pump with a flow rate of 0.17 dm^3/min for feeding the water and saturated saline solution (Figure 2e—2).
- Peristaltic pump with a flow rate of 0.08 dm^3/min for pH adjustment, introducing catholyte into the anolyte exiting the cell (Figure 2e—4).
- Pump with a flow rate of 0.02 dm^3/min for introducing the saturated solution into the cell (Figure 2e—3).



(a) (b) (c)
(d) (e)

Figure 2. Main components of the system: (**a**) control panel; (**b**) resin filter and saturated saline (NaCl) tank; (**c**) flow rate regulation gauge; (**d**) brine tank; (**e**) EW production and liquid handling system with electrolytic cell (1) and peristaltic pumps (2–4).

The fruit and vegetable washing system used for testing consisted of the following:

- A 300 L food-grade plastic tank (Figure 3a).
- A 100 dm^3/min pump for recirculating the sanitizing solution composed of groundwater and AEW (Figure 3b).
- Piping for recirculating water from the bottom to the top of the tank (Figure 3c,d).

The electrolyte cell of the generator consisted of an external titanium structure, an anodic electrode (Ruthenium-Iridium), and a cathodic electrode (Titanium), separated by a ceramic septum with an average pore size of 0.2 μm. The electrodes had a total active surface area of 1.5 cm^2 and a thickness of 1.0 mm. The electric current absorption of the cell varied between 5 A and 5.2 A, powered by a 12 V DC supply; the pressure gauge located downstream of the resin filter was calibrated to 1.0 atm.

Figure 3. Prototype of the washing system at Novus in Brindisi (BR): (a) a 300 L food-grade plastic tank; (b) recirculation pump for the sanitizing solution; (c) inlet and outlet piping system from the pump; (d) re-entry pipe for the sanitizing solution into the tank.

A schematic representation of the flow processes within the electrolyte cell is shown in Figure 4.

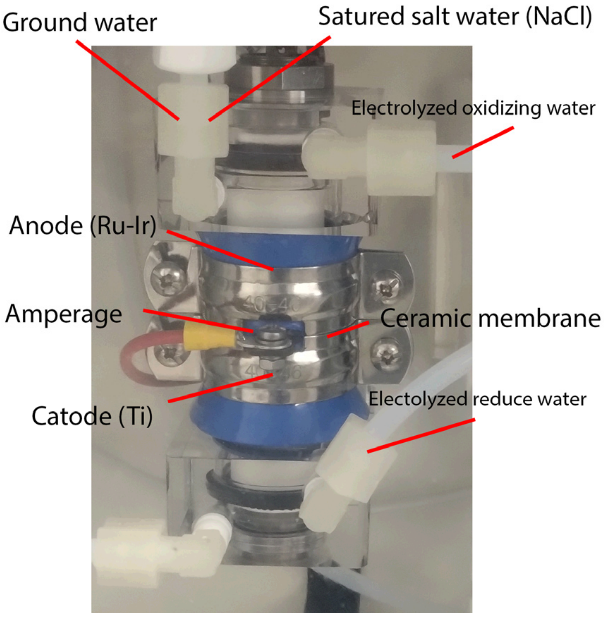


Figure 4. Schematic representation of the electrochemical activation process of salted water.

Electrolysis of the groundwater and saturated NaCl solution induced dissociation of the salt into sodium ions (Na^+) and chlorine ions (Cl^-) as they passed between the electrodes, forming hydroxide ions (OH^-) and hydrogen ions (H^+) in various proportions. The OH^- and Cl^- ions migrated towards the anode, where oxidation occurred, producing chlorinated compounds such as HOCl, ClO, and HCl, as well as gaseous O_2 and Cl_2. Conversely, the Na^+ and H^+ ions migrated towards the cathode, where they underwent chemical reduction, yielding sodium hydroxide (NaOH) and a minor amount of gaseous H_2. As a result, two types of electrolyzed water (EW) were simultaneously generated: an acidic solution at the anode (anolyte) and a basic solution at the cathode (catholyte). The pH was potentially regulated by the switch located on the control panel (Figure 2a); the set pH value determined the volume of catholyte added to the outgoing anolyte solution (Figure 2e). The set pH can range from 0 to 11, controlled by internal generator software that adjusted the peristaltic pump flow rate for introducing catholyte as it exits the electrolyte cell (Figure 2e). Based on the in vitro test results [17], acidic electrolyzed water (AEW) was produced by setting a pH value of 5 on the generator's control panel and operating at an inlet solution flow rate of 1.0 atm to the electrolyte cell. The electrolyte cell produced an AEW volume of 30–32 L, required to obtain 300 L of a 10% sanitizing solution in groundwater (Figure 3a). The pH, electrochemical oxidation potential (EOP), and free chlorine content of the solution in the tank were measured to assess the operating parameters during sanitization. Chlorine concentrations (mg/L) were determined using a photometric test (Model HI97101, HANNA Instruments, Romania); the pH and electrochemical oxidation potential (EOP) were determined using a benchtop pH meter (POCTME Multifunction—eVatmaster Consulting GmgH—Frankfurt am Main—Germany). For each washing activity, samples were collected in the tank with a 50 mL Falcon tube before, during, and at the end of the washing process (Table 3)

Table 3. Analytical parameters of groundwater used.

Groundwater	Time 0	Time 9 h
pH sanitizing solution	7.42	7.40
Free chlorine (mg/L)	1.80	1.78
EOP (mV)	−6.30	−6.25

2.2. Activity of Electrolyzed Water on Disease Development on Produce

The sanitizing solution was tested on apparently healthy fresh produce from organic farming, purchased from local vendors on the same day as the treatment. Fruits and vegetables were artificially wounded using a wounding tool (3 mm × 3 mm wounds) and inoculated before the washing phase in the tank containing the sanitizing solution (Figure 3a). The pathogens used in the tests included *Penicillium expansum* (Pex04), *Aspergillus niger* (ASP03), *Alternaria alternata* (A20), and *Botrytis cinerea* (Bc28), from the collection of the Department of Soil, Plant and Food Sciences (DiSSPA) at the University of Bari Aldo Moro, Italy, cultured on potato dextrose agar (PDA, Oxoid, Milan, Italy). The inoculum was prepared by flooding the plates with 7 mL of 0.01% Tween 20 (Merck, Milan, Italy), gently scraping the colony surface using a sterile spatula, and passing the suspension through a sterile gauze layer. The conidial concentration was determined using a Thoma counting chamber (HGB Henneberg-Sander GmbH, Lutzellinden, Germany) and adjusted to 10^5 conidia per mL for all pathogens tested. Fresh produce was inoculated by placing 25 µL of conidial suspension into the wounds, made as described above, and allowing them to dry at room temperature for approximately 1 h before treatment with electrolyzed water. Following the electrolyzed water treatment (about 2 min of dipping in the sanitizing solution), the products were left to dry for approximately 1 h, packed in designated trays sealed in plastic bags, and stored at room temperature (26 ± 2 °C). The observation period for the onset and development of rot ranged from 1 to 21 days, depending on the rot susceptibility to the pathogens of the produce tested. Groundwater was used in the control experiments instead of electrolyzed water. Data on rot development on various produce were reported as the mean of five replicates, ± standard error of mean (SEM), each made by ten fruit/leaves/young apex, depending on the produce.

2.3. Mass and Energy Balance Evaluation

A mass balance was conducted on the production of AEW with optimal physicochemical properties for sanitization. The mass balance involved measuring the volume of incoming groundwater, the volume of the saturated NaCl solution, and the output volumes of the anolyte and catholyte effluents, corresponding to the pH value set on the machine's control panel. The energy balance was assessed by measuring the active electric power absorbed by the prototype during production. To accomplish this, an energy meter with data-logging functionality (CW121, Yokogawa, Tokyo, Japan) was used; this device allowed for the measurement of energy consumption for single-phase loads, considering the possible load imbalance across each phase. Measurements were taken by placing the instrument's current probes in the electrical line between the switchboard and the general power supply for the machine and the electrolyte cell, respectively. Energy consumption values were also converted into economic costs based on the current energy market rates in Italy [36]. A comparison was thus made with the energy costs associated with industrial sodium hypochlorite production [37–39], which is currently available in suitable formulations for industrial sanitation systems.

3. Results and Discussion

3.1. Determination of Sanitizing Solution Activity Parameters

The main analytical characteristics of the sanitizing solution are presented in Table 4. This solution was prepared using 10% AEW, produced by setting the parameters listed in Table 2, and 90% groundwater, with its analytical parameters detailed in Table 3.

Table 4. Analytical parameters of wash water with 10% AEW (mean values obtained with no. 3 repetitions).

10% AEW at 300 L Groundwater Volume	Time 0	SD	Time 5 h	SD	Time 9 h	SD
pH sanitizing solution	7.27	0.03	7.35	0.01	7.53	0.03
Free chlorine (mg/L)	3.26	0.02	4.30	0.06	5.00	0.07
EOP (mV)	−0.40	0.04	−7.53	0.02	−16.60	0.03

Compared to the laboratory tests using distilled water, groundwater, essential for producing larger volumes than those feasible in laboratory settings (Table 3), demonstrated a buffering effect on the sanitizing solution, resulting in a neutral pH throughout its use period (Table 3). During the observation period, the EOP values ranged from −0.40 to −16.60 mV (Table 4), likely due to increased free chlorine dissociation, which varied from 3.26 to 5.00 mg/L (Table 4). These values tend to create a neutral environment, in contrast to the acidic environment that characterized previous in vitro tests [17].

It should be noted that the characteristics of water used in an industrial process may vary depending on the natural salt content. Therefore, in the industrial production of AEW, facilities must provide appropriate control systems and standardize the input water parameters for the generator to ensure that the generator's anolyte effluent meets the required parameters for producing an effective sanitizing solution. Regarding the effluents associated with this type of production, the sanitizing water used is not acidic and has pH values (Table 4) compliant with wastewater discharge regulations: a pH between 5.5 and 9.5 [36]. In the event of excessive anolyte discharge due to a generator malfunction, neutralization could still be achieved by mixing unused catholyte water. A limiting factor for effluent discharge is the active free chlorine content (Table 4), which in this case is relatively above the regulatory limit [36]. However, prior to discharge, measured values can be easily adjusted to comply with limits through suitable physicochemical treatments (e.g., sulfite-based treatments). In contrast, chlorine levels in solutions typically used for post-harvest industrial sanitation are significantly higher and require more costly physicochemical treatments [38].

3.2. Inhibitory Activity on Rot Development on Produce

Figures 5–8 show the results obtained from tests on fresh produce. Compared to the control, the treated wounds exhibited a reduction in infections of between 85% and 90% over the 21-day incubation period (Figures 5–8), depending on the susceptibility of the treated produce to various pathogens.

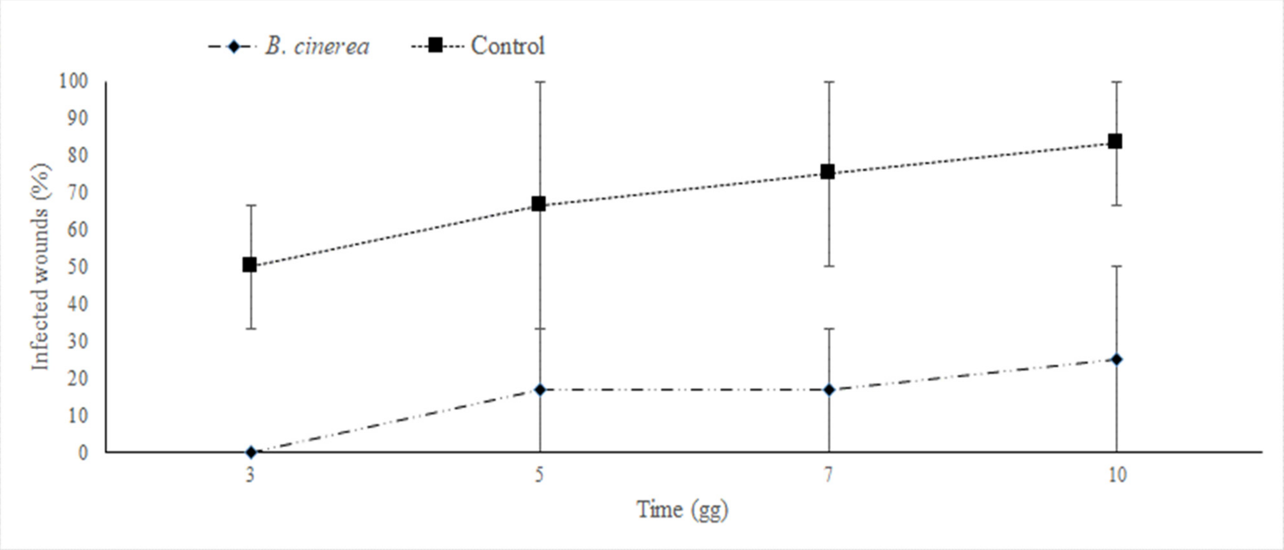


Figure 5. Percentage of wounds infected by *Botrytis cinerea* on beetroot leaves as a function of storage time (3–10 days). After pathogen inoculation, beetroot leaves were treated with 10% AEW sanitizing solution and kept at room temperature for 10 days. Bars represent the mean of five replicates ± standard error of mean (SEM) (Table 4).

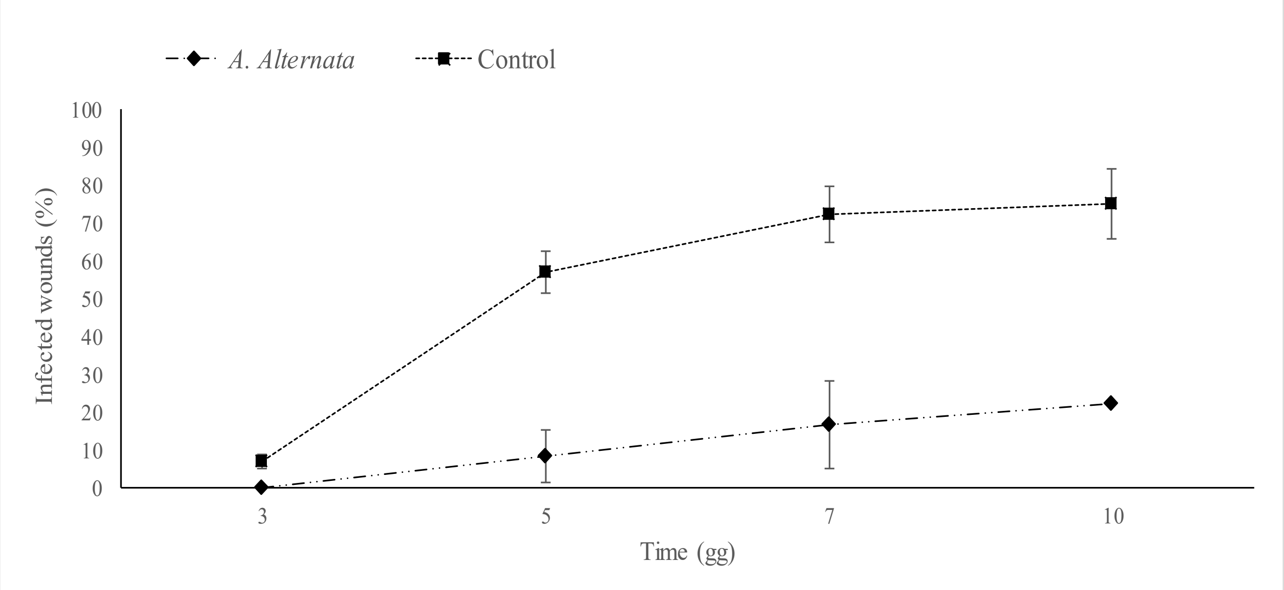


Figure 6. Percentage of wounds infected by *Alternaria alternata* on cherry tomatoes as a function of storage time (3–10 days). After pathogen inoculation, cherry tomatoes were treated with 10% AEW sanitizing solution and kept at room temperature for 10 days. Bars represent the mean of five replicates ± standard error of mean (SEM) (Table 4).

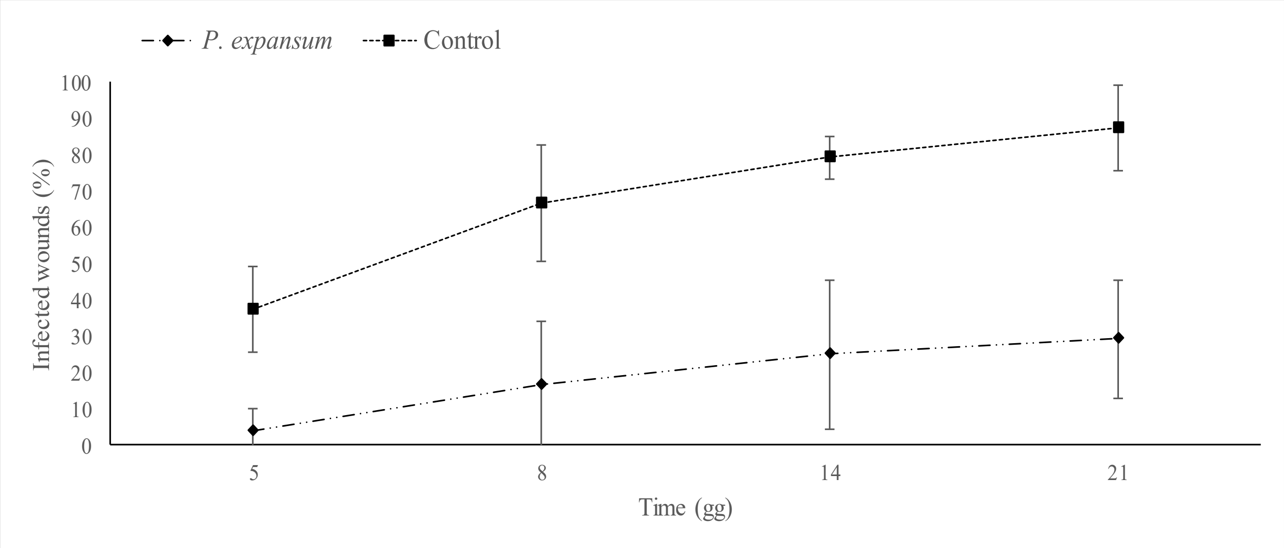


Figure 7. Percentage of wounds infected by *Penicillium expansum* on Golden Delicious apples as a function of storage time (5–21 days). After pathogen inoculation, Golden Delicious apples were treated with 10% AEW sanitizing solution and kept at room temperature for 21 days. Bars represent the mean of five replicates ± standard error of mean (SEM) (Table 4).

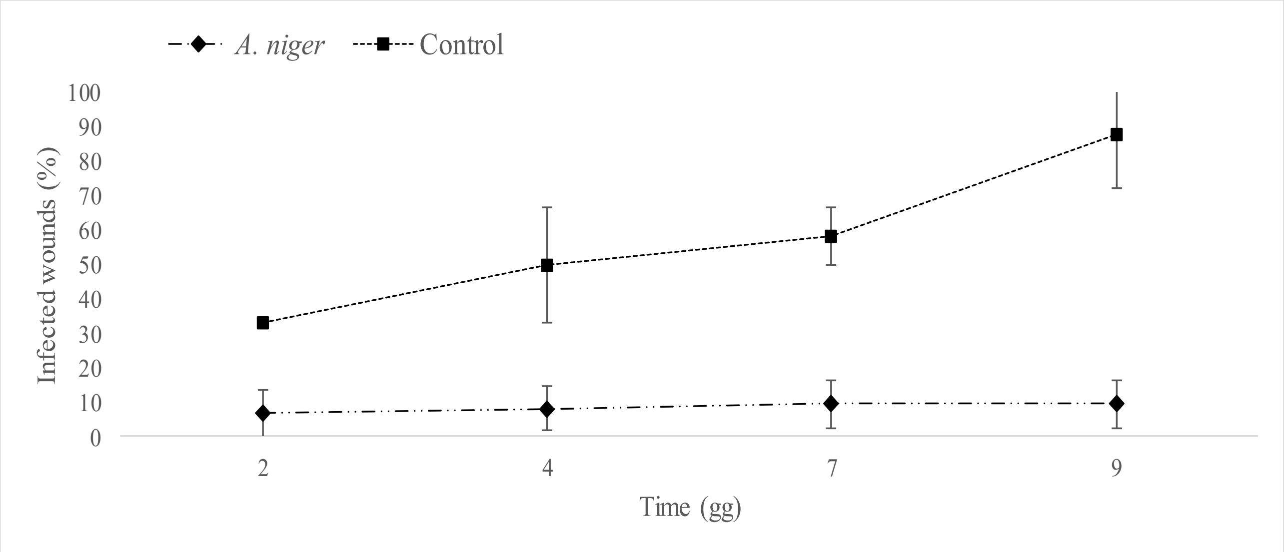


Figure 8. Percentage of wounds infected by *Aspergillus niger* on chicory leaves as a function of storage time (2–9 days). After pathogen inoculation, chicory leaves were treated with 10% AEW sanitizing solution and kept at room temperature for 21 days. Bars represent the mean of five replicates ± standard error of mean (SEM) (Table 4).

Thus, the observed results demonstrate that in an initial environment with a pH of 7.27 (approaching neutrality), free chlorine concentration of 3.26 mg/L, and an EOP of −0.40 mV, a significant reduction in disease development was achieved for the various tested pathogens. This reduction likely results from mechanisms not fully understood, but possibly involving alterations in the cell membrane permeability of conidia, thereby affecting their physiology [31]. Additionally, a slightly negative EOP, as seen with basic sodium hypochlorite-based compounds commonly used for sanitation, may have influenced the production of metabolic compounds, such as ATP. Oxidizing compounds likely damaged cellular lipid membranes, denatured internal proteins, and inhibited cellular replication through DNA degradation, thus hindering enzymatic activity [32,33].

Therefore, although further trials on the same scale used here are needed, the use of a minimum of 10% AEW in a 300 L sanitizing solution with a pH of 7.27, an EOP of −0.40 mV, and free chlorine at 3.26 mg/L proved effective against certain rot-inducing agents on fresh produce compared to groundwater alone. Consequently, the use of AEW in solution may meet industrial sanitation needs and ensure continuity in washing lines. The solution's activity parameters showed good stability over approximately 9 h during functional parameter monitoring. Thus, reusing the same washing water for the entire work period, with suspended material filtration and AEW replenishment, may maintain the same volume of sanitizing washing solution throughout the production cycle, possibly extending over multiple days, which would save considerable water and energy.

Regarding effluents from this type of production, the sanitizing water used had less acidic pH values than typically allowed under wastewater discharge regulations. It is also notable that this study used groundwater, which showed a significantly higher buffering effect (Table 3) than previous studies using distilled water, where inhibition levels were similar, but effluent pH was notably more acidic [17].

3.3. Mass Balance Evaluation

Table 5 presents the mass balance to produce acidic electrolyzed water (AEW), using a generator setting of pH 5 and a flow rate of 10 L/h.

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

pH	Flow Rate (L/h)	Brine (L)	Main Water (L)	Anolyte Produced: AEW (L)	Catholyte as Difference (L)
5	10.0	0.1	9.9	7.5	2.5

With a flow rate of 10 L/h of tap water through the EW generator, 0.1 L of saturated NaCl solution was consumed, yielding 7.5 L of usable anolyte and 2.5 L of catholyte as waste, which could potentially be recycled for cleaning facilities and work tools. The reduction was notable, given that, based on the results obtained (Figures 5–8), the AEW to sanitizing solution mix ratio was 1:10, or approximately 100–110 L/m^3.

The AEW generator used during production had an average power consumption of 84.4 W (Figure 9), with most active power, averaging 49.3 W, consumed by the electrolytic cell itself (Figure 10). The remaining 35.1 W was associated with the active power needs of other generator components, namely, power circuits and peristaltic pumps that handled the flow of tap water, saturated NaCl solution and catholyte.

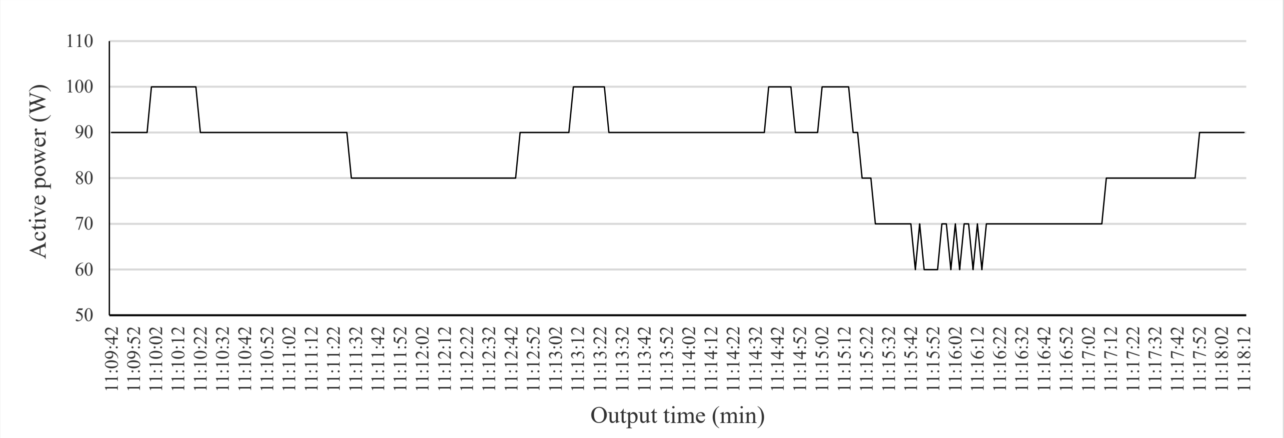


Figure 9. Global active electrical power absorption of the AEW generator, as a function of time.

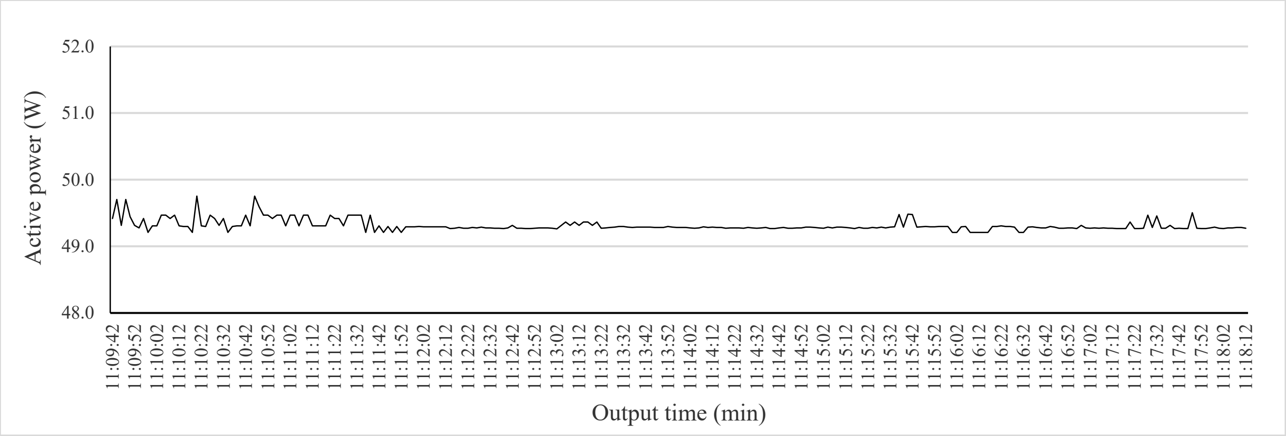


Figure 10. Global active electrical power absorption of the electrolytic cell, as a function of time with intensity of electric current of 5.2 A.

The stepped pattern in overall power consumption (Figure 9) reflects the stabilization of the set pH value, achieved by varying the saline solution pump speed initially and later by adjusting the pH correction pump. By contrast, the water feed pump operated at a continuous, steady rate. Consequently, the generator's minimum power draw, below 70.0 W (Figure 9), only occurred for short intervals (30 to 120 s) when set values remained stable and no pH adjustment was needed.

Thus, the pumps for the saturated NaCl solution and catholyte (Figure 2e—3 and 4) are critical components in EW generators, even in higher-capacity units. These pumps are small and designed for low flow rates but operate under intermittent, wear-inducing conditions due to the nature of the effluent, frequent changes in rotation speed and pulsation. Therefore, the design of EW generators should include appropriate control and maintenance systems for optimal machine management.

The time required to produce 10.0 L of AEW was 80.0 min, with an average active power consumption of 112.5 W, corresponding to an electricity consumption of 0.15 kWh and a specific energy usage of 15.0 kWh/m^3 of AEW (Table 6). For the electrolytic cell alone, the average active power usage represented 58.4% of the total power consumed, and both the energy consumption and specific energy usage made up 60% of the total.

Table 6. Average energy parameters, related to generator and the electrolytic cell, relating to the production of 10.0 L of AEW at pH 5.11, EOP 205 mV, and free chlorine >8mg/L.

Machine Components	Process Duration	Average Active Power	SD	Energy	Specific Energy
Electrolyzed water generator	80 min	112.5 W	10.0	0.15 kWh	15.0 kWh/m$^3_{EW}$
Electrolytic cell	80 min	65.7 W	0.01	0.09 kWh	9.0 kWh/m$^3_{EW}$

In energy terms, the industrial production of 14–15% sodium hypochlorite (NaClO) typically involves the electrolysis of a saline solution, yielding Cl_2 and H_2 gases as well as NaOH in an aqueous solution via chlor-alkali electrolysis (ECA). A standard ECA process consumes about 2.100–3.000 kWh to produce 1.0 m^3, where the energy cost of generating 1.0 m^3 of Cl_2 accounts for approximately 51–58% of the total energy consumption [38,39], amounting to about 1.740 kWh at maximum values (Table 6). Thus, the energy cost to produce 1.0 m^3 of a 14% sodium hypochlorite solution is around 325 kWh (Table 7).

Table 7. Energy parameters relating to the production of AEW, $NaClO_2$ industrial, and $NaClO_2$ at 14%.

	Average Active Power	Work Time	Electrical Energy Absorbed	Specific Electrical Energy
Generator EW	112.5 kWh	80 min	150.0 kWh	150 kWh/m^3 AEW
ECA $NaClO_2$	1740 kWh	80 min	2.320 kWh	2.320 kWh/m^3
$NaClO_2$ 14%	244 kWh	80 min	325 kWh	325 kWh/m^3

In comparison, producing AEW requires only 46.1% of the energy cost of a conventional industrial sanitizing solution (Table 6).

For a 14% $NaClO_2$ solution, the energy cost is 325 kWh/m^3 (Table 7), while producing an AEW-based sanitizing solution at pH 7.27 requires just 150 kWh/m^3 (Table 7). This energy saving is also reflected in economic terms, with AEW production costs at EUR 18.78/m^3 compared to EUR 40.69/m^3 for a 14% $NaClO_2$ solution (Table 8).

Table 8. Energy and economic parameters relating to the dilution in a sanitizing solution of 1.0 m^3. * Gross price c€/kWh 12.52 [40].

	Energy Cost	* Gross Price c€/kWh 12.52	Cost 10% AEW Solution	Cost 5% Sodium Hypochlorite 14% Solution
EW generator	150 kWh/m^3 EW	18.78 €/m^3 EW	1.88 c€ *	
ECA $NaClO_2$	2320 kWh/m^3 $NaClO_2$	290.46 €/m^3 $NaClO_2$		
$NAClO_2$ 14%	325 kWh/m^3 $NaClO_2$	40.69 €/m^3 $NaClO_2$		2.03 € *

Overall, sodium hypochlorite-based sanitation methods are highly energy-intensive and environmentally impactful. Due to the use of mercury-based electrolytic cells and the generation of toxic sludge in nearly all production processes, hypochlorite solutions typically allow for only a few cycles in wash tanks [38,39,41]. In contrast, AEW-based methods operate intermittently, with 1.0 m^3 of AEW being sufficient to maintain sanitation processes over several workdays in a fresh produce facility. AEW sanitizing water can also be filtered to remove solid residues, allowing it to be reused across multiple wash cycles with only minimal AEW replenishments required.

4. Conclusions

The small-scale trial conducted on fresh produce, based on prior in vitro experimental results, showed outcomes consistent with previous studies [17]. Specifically, treatment with AEW demonstrated an 85–90% inhibition of rot development on fresh produce, achieved with approximately 2 min of immersion washing and incubation periods ranging from 2 to 21 days. These results were obtained using a 10% AEW sanitizing solution in groundwater with the following characteristics:

- AEW solution: pH 5.11, EOP 205.0 mV, free chlorine >8.0 mg/L.
- Groundwater: pH 7.42, EOP −6.3 mV, free chlorine 1.80 mg/L.
- Washing solution: pH 7.27, EOP −0.40 mV, free chlorine 3.26 mg/L.
- Final volume: 300 L.

Thus, even in small-scale trials, a sanitizing solution containing at least 10% AEW can be considered a viable alternative to current post-harvest sanitization standards, which typically rely on chemical agents.

The energy consumption was found to be 150 kWh/m^3 of AEW, significantly lower than that required to produce 14% sodium hypochlorite solutions (325 kWh/m^3), which are commonly used as industrial sanitizers for washing fruits and vegetables. Environmentally, the AEW production method and the potential to reuse the water across multiple wash cycles offers a reduced impact compared to conventional sanitizing solutions used in post-harvest processing. Moreover, the effluent from AEW production/use has a neutral pH and chloride content suitable for legal discharge; however, its free chlorine concentration is slightly above allowable limits, requiring minimal chemical treatment of the wastewater before discharge.

The design of AEW generators for post-harvest applications should include specific control and management systems to standardize input water parameters and minimize wear on the saturated NaCl solution and catholyte pumps. These pumps face frequent variations in rotation speed, pulsations, and the challenges posed by the chemical nature of effluents.

In conclusion, electrolyzed water can be regarded as a viable alternative for washing water sanitization and for inhibiting rot development on fresh produce in post-harvest handling. It offers real potential for reducing operational and wastewater disposal costs.

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