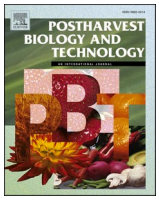
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# Electrical stimulation of table grape berries as new alternative for postharvest *Escherichia coli* contamination management

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ABSTRACT

With a growing global population, food demand is rising, yet large amounts of food are lost to spoilage each year. Unpredictable weather, pest and pathogen pressures, and poor storage contribute to nearly one-third of all food going to waste. Reducing spoilage is crucial to meet population needs, conserve resources, and enhance food security. The application of postharvest antimicrobial agents can efficiently reduce spoilage; however, sustainable alternatives, are increasingly being sought for their lower environmental impact. This study presents a lab-developed setup that uses low electrical currents to inhibit *Escherichia coli* growth on fruit. When an alternating current (50 mA) was applied to *Escherichia coli*-contaminated grapes, 99 % of the bacteria were eliminated. After 12 days, visual inspection showed that untreated, contaminated grapes had rotted, while the electrically treated ones remained visually similar to uncontaminated grapes. Quantitative Colony Forming Unit (CFU) reduction assays and Scanning Electron Microscopy (SEM) analysis of grape skins confirmed these findings, showing clear bacterial structural damage on treated grapes, indicating the electrical current's effectiveness in deactivating *Escherichia coli*. These promising results highlight the potential of this eco-friendly decontamination strategy and make it adaptable to grapes and other fruits and vegetables.

## 1. Introduction

Microbiological food safety is a pressing concern for both public health and the economy. According to the World Health Organization (WHO), one in every 10 people worldwide suffers from foodborne illnesses each year, leading to around 420,000 deaths annually (Owusu-Apenten and Vieira, 2023; World Health Organization, 2019). A common and dangerous contaminant is *Escherichia coli* (*E. coli*), a bacterium often found in undercooked food and contaminated water. *E. coli* infections can cause severe gastrointestinal illness and, in certain strains, potentially life-threatening complications like hemolytic uremic syndrome (HUS) (Bruyand et al., 2018; Luna-Guevara et al., 2019). To prevent infections and ensure food safety, large amounts of food are often discarded when contamination is suspected or detected. This precautionary approach, combined with spoilage from factors like poor storage, handling, and display conditions, contributes to an estimated 45 % of global fruit and vegetable waste each year. This significant loss impacts both food security and the environment, underscoring the need for improved handling and preservation practices (Elik et al., 2019).

Postharvest infection control, due to the presence on table grapes of fungal diseases such as *Botrytis cinerea* and *Aspergillus* spp., is often managed with the use of fungicides. However, combined with excessive costs, they may have unexpected repercussions on human health and environment due to their high biological activity and persistence, which is forcing EU (Directive 2009/128/EC) to ban many synthetic agrochemicals, establish rules for sustainable use of agrochemicals and explore new alternatives. These approaches refer to an arsenal of new, non-chemical solutions, to combat fruit and vegetable diseases, promoting food production and conservation (D'Addabbo et al., 2014; Di Canito et al., 2021; Maroni et al., 1999). A promising solution involves using physical agents rather than chemical ones, as potential substitutes for pesticides (Marian Darma et al., 2022).

In recent years, decontamination through the application of physical agents, such as ultrasound and direct electrical current has been gaining

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ground. Taking advantage on the cavitation phenomenon, ultrasounds have been applied in food industry to fresh fruits and vegetables for the inactivation of microorganisms such as *Salmonella* spp., *Listeria monocytogenes*, *E. coli* O157: H7, *Aeromonas* and the hepatitis A virus. The growth and collapse of bubbles due to cavitation, generating a localized mechanical and chemical energy, has been recognized the reason for the antimicrobial properties (São José et al., 2014).

Electric current has been also studied as an alternative to chemical disinfectants for inhibiting and/or killing microorganisms since the 1960s. Electric current is emerging as a promising tool for the development and optimization of innovative approaches to water and food disinfection and preservation, although its application is still in its early stages. The primary goal of these methods is to reduce or eliminate some of the commonly unwanted microorganisms present (Krishnamurthi et al., 2020; Ranalli et al., 2002; Valle et al., 2007).

Some studies have reported the effects of low electric current on yeast cells. Ranalli et al. (2002) found that 10, 30 and 100 mA, with the electrode positioned at the bottom of the well, could reduce the adenosine triphosphate (ATP) content and the viability of suspension cultures of *Saccharomyces cerevisiae* and *Hanseniaspora guilliermondii*. Furthermore, the low electric current treatment of *S. cerevisiae* resulted in cytoplasmatic membrane integrity degradation (Ranalli et al., 2002). Another study showed that when applying 200 or 2000 μA for 4 days, to electrodes inserted 3 mm from discs with pre-formed biofilms, several strains of *Candida glabrata* and *Candida albicans*, respectively, showed a significant reduction in biofilm (Schmidt-Malan et al., 2015).

Bacterial biofilms from *Staphylococcus epidermidis, Staphylococcus aureus* or *Pseudomonas aeruginosa* adhered to discs have been treated by placing an electrode positioned on both sides of the disc at 3 mm and by applying 200 μA. The results showed a reduction in microbial viability due to changes in cell morphology and possibly due to the generation of reactive oxygen species (ROS). An increase in ROS production by *S. aureus* and *S. epidermidis* biofilms following exposure to direct current has been observed (Brinkman et al., 2016). Valle et al. (2007) also showed that there was a notable inhibition of enzyme activities, growth and a reduction in the ATP content of the *E. coli* bacterial suspension using electrical currents at 20 and 40 mA. The test was conducted in cylindrical glass tanks measuring 20 cm in diameter and 10 cm in height, with electrode pairs positioned 19 cm apart within the tanks (Valle et al., 2007).

In the present work, an innovative setup was designed in the lab to explore the effects of alternating current (50 mA) applied through electrodes surrounding a grape previously contaminated with *E. coli* and immersed in a 0.9 % NaCl solution as electrolyte. The effects of the low electric current intensity on bacterial viability were evaluated using conventional cultural method (viable cells counts), visual assessment and SEM analysis of the grape's skin. This study demonstrates the potential of using electric stimulation on fruit as an effective postharvest infection management strategy, helping to reduce early spoilage caused by microbial contamination.

## 2. Materials and methods

### 2.1. Microorganisms and media

Pure cultures of *E. coli* (CIP 110067) were used. Laboratory bacterial assays were performed in Tryptic Soy Broth (TSB) medium (Merck, Darmastadt, Germany). The bacteria were first grown at 37 °C overnight with orbital rotation at 250 rpm.

On the following day, the pre-inoculum underwent centrifugation at 5000 rpm for 5 minutes, followed by two washes with fresh medium. The optical density was measured at 600 nm ($OD_{600}$) and adjust to 0.1 ± 0.01 using TSB medium, resulting in a working inoculum of approximately $7 \times 10^7$ CFU/mL.

### 2.2. Table grapes washing and E. coli contamination

The table grapes (variety: Thompson Seedless) used in this study were purchased from a local supermarket. To prevent interference from their own microbiota during tests with *E. coli*, the grapes were initially washed in a cleaning solution containing 0.05 % (v/v) sodium hypochlorite (bleach) for 1 h at 500 rpm, followed by thorough rinsing with water to ensure all bleach was removed. For the *E. coli* contamination process, a sterile 12-well plate was used, with each well containing a single grape berry submerged in an *E. coli* solution at an $OD_{600}$ of 0.1. The plate was then incubated overnight, i.e. approximately 12 h, at 37 °C.

### 2.3. Electrical stimulation setup

A setup was assembled to deliver a precise electrical alternating current to the grape berries, using a 0.9 % NaCl solution as the electrolyte for the electrical stimulation. This setup, schematically represented in Fig. 1, consists of two Teflon discs positioned above and below a network of 12 silver electrode wires (0.3 mm diameter), which serve as electric conductors. Placed between the discs and inside the network of wires are the grapes, serving as the study elements. Within the network, consecutive wires act as opposite electrodes (6 anodes and cathodes, alternately actuated), creating a repeating pattern around the grapes (Fig. 1). Electric insulators were placed at contact points to ensure that wires with opposite charges do not come into contact. This configuration was designed to establish multiple current flow points and form a network around the whole grape berry. Teflon discs were selected for the construction of the setup apparatus due to their biological inertness (Korzinskas et al., 2018; Schmidt-Malan et al., 2015). On the other hand, silver wires were used to conduct the electrical current since it is an inorganic material renowned for its antimicrobial properties and high electrical conductivity (Chouirfa et al., 2019; Holler et al., 2007).

### 2.4. In vitro electrical stimulation of grapes

After overnight contamination with *E. coli*, the grape berries were individually treated in a well of a sterile 12-well plates (0.025 $cm^2$ area) through the application of a defined electrical current using a current generator (Gamry®600 + Potentiostat/Galvanostat/ZRA, Gamry Instruments, Inc., Warminster, PA, USA). The Gamry®600 + was programmed to deliver a constant current of 50 mA with polarity inversion every 1 s for 10 min (300 cycles) while monitoring the potential variation. This electrical density was selected based on previous studies indicating that current as low as 25 mA can effectually kill the *E. coli* bacteria (Pareilleux and Sicard, 1970). Before and after each assay, the Teflon disks and electrode network device were sterilized by subjecting them to 30 minutes of ultraviolet (UV) light exposure. For the experiments, each contaminated grape was placed inside and in contact with the electrode network of the actuator and submerged in 3 mL of a sterile NaCl 0.9 % (w/v). Two control groups were tested: (i) grapes that were not contaminated and only underwent initial washing, and (ii) contaminated grapes that did not receive any current application. All tested grapes, including controls, were divided into two groups for: visual assessment over time and quantitative assessment using the Colony-Forming-Unit (CFU) assay. Six replicates were performed for each sample.

### 2.5. Assessment of the impact of electrical current on contaminated grapes

#### 2.5.1. Qualitative analysis

To visually assess the grapes, all samples—including contaminated controls, washed controls, and those treated with electricity—were promptly sealed in sterile zipper bags, where their contamination and degradation were observed over time. The impact of electrical stimulation on bacterial structural and morphology alterations on grapes was




**Fig. 1.** Experimental setup assembled to assess the effectiveness of the electrical stimulation of grape berries as alternative approach for managing postharvest contamination. The green wires indicate the positive electrode, while the black wires represent the negative electrode, both submerged in a 0.9 % NaCl solution serving as the electrolyte.

investigated using scanning electron microscopy (SEM) (JEOL JSM-6010LV). After the test, the skin of the grapes subjected to electric alternating current and the respective controls (contaminated grape not subjected to current and washed grape) were removed and fixed with a fixative solution of 2.5 % glutaraldehyde and gradually dehydrated by a graded series of ethanol, 40 %, 70 %, 90 %, 100 %. Prior to SEM observation, the grape skins were coated with gold (gold sputtering equipment: Quorum/Polaron model E6700; acceleration voltage of 5.00 kV).

### 2.5.2. *Quantitative analysis*

For a quantitative study, the grapes exposed to electrical alternating current were promptly washed in a 3 mL of a NaCl sterile solution (0.9 % (w/v)) for 30 min at 500 rpm. The two controls were submerged for 10 min in a 0.9 % (w/v) NaCl sterile solution (to remain in the same conditions as the stimulated grapes) and subsequently washed in 3 mL of a NaCl sterile solution (0.9 % (w/v)) for 30 min at 500 rpm. The suspensions obtained were subjected to 8 serial dilutions (1:10) in a sterile 0.9 % (w/v) NaCl solution. For each dilution, a volume of 20 µL was dropped on Nutrient Broth (NB, Merck, Darmastadt, Germany) plate agar and further incubated at 37 °C for 24 h. For this assay, NB agar medium was selected due to its simple and universally applicable composition, which provides the essential nutrients required for the growth of non-fastidious bacteria such as *E. coli*. Furthermore, its composition minimizes the risk of promoting the proliferation of opportunistic contaminants that could compete with *E. coli* and compromise the experimental results. The versatility of the medium allows for consistent bacterial growth, making it particularly suitable for colony forming unit (CFU) assays. Furthermore, the moderate growth dynamics associated with NB agar facilitates accurate colony counting, a critical factor in ensuring the reliability and accuracy of CFU studies (Brito-Pereira et al., 2024; Low et al., 2013; Moreira et al., 2022). Thus, the number of viable bacteria was determined, allowing a quantitative analysis of the average CFU/mL. The bactericidal activity was evaluated with three independent assays as $\log_{10}$ for each condition.

### 2.6. *Statistical analysis*

The results were statistically analyzed, and the average of individual measurements with the respective standard deviations was used. The significance of differences between contaminated grapes and electrically treated grapes was assessed using Student's *t*-test. The tests were performed using the software GraphPad Prism version X for Windows (GraphPad Software, San Diego, CA, U.S. A.).

## 3. Results and discussion

Individual grape berries were exposed to electrical stimulation to demonstrate the potential of non-chemical methods in preventing microbial-induced decay in grapes. For that, a setup was designed and assembled to allow the application of an electrical alternating current on the surface of each grape berry (Fig. 1). It was essential to ensure that the grape skins remained intact with no leakage from the interior, as the inside of the grape may also be colonized by its own microbiota.

Fig. 2 illustrates a 100-second segment of the electric treatment acquired by the Gamry software. Throughout the process, the alternating current remained constant at approximately ± 50 mA, thanks to the device's built-in adjustment mechanism that ensures a constant electric current. According to the experimental setup designed for the electricity study (Fig. 1), despite the applied current is 50 mA, it is distributed among the 12 wires that surround the grape, resulting in approximately 4.17 mA passing through each wire.

Slight potential variations were observed, with maximum and minimum values recorded at −91.93 mV and −88.87 mV, respectively. These potential fluctuations may be attributed to changes in resistance within the circuit/medium. According to Ohm's Law ($V = I \times R$), if the maximum current (I) remains constant while the potential (V) varies, it indicates a change in resistance (R) within the circuit (Carter, 2013). The presence of adherent cells in the grape and in the surrounding medium can affect the current flow by either increasing or decreasing the resistance of the circuit/medium. The magnitude of this resistance depends on the number and size of the bacteria and can also be influenced with metabolic activity and the extracellular polymeric substance that acts as an insulating layer (Gutiérrez et al., 2016; Paredes et al., 2014).

As previously stated, the contamination of the grapes was carried out in a controlled manner, ensuring that all grapes were exposed to the same bacterial concentration for the same duration, to guarantee effective and widespread surface contamination across all grapes. Then, individual grape berries were electrically stimulated under the previously described controlled alternating current conditions to demonstrate the potential of alternative non-chemical methods for preventing microbial-induced rotting in grapes. It was essential to assure that each intact grape was totally submerged in the electrolyte NaCl 0.9 % solution to achieve uniform electrolysis across the surface of the grape. Thus, the antibacterial tests were conducted on contaminated grape berries to assess the effectiveness of low electrical alternating current to eradicate the clinically relevant Gram-negative bacteria *E. coli* previously attached to the berry's surface. The results were then compared to the controls. This bacterium was utilized as a representative model for Gram-negative bacteria to mimic *Rhizobium* (*Agrobacterium*) *vitis*, one of the most pathogenic bacteria affecting vines and a known cause of gall disease

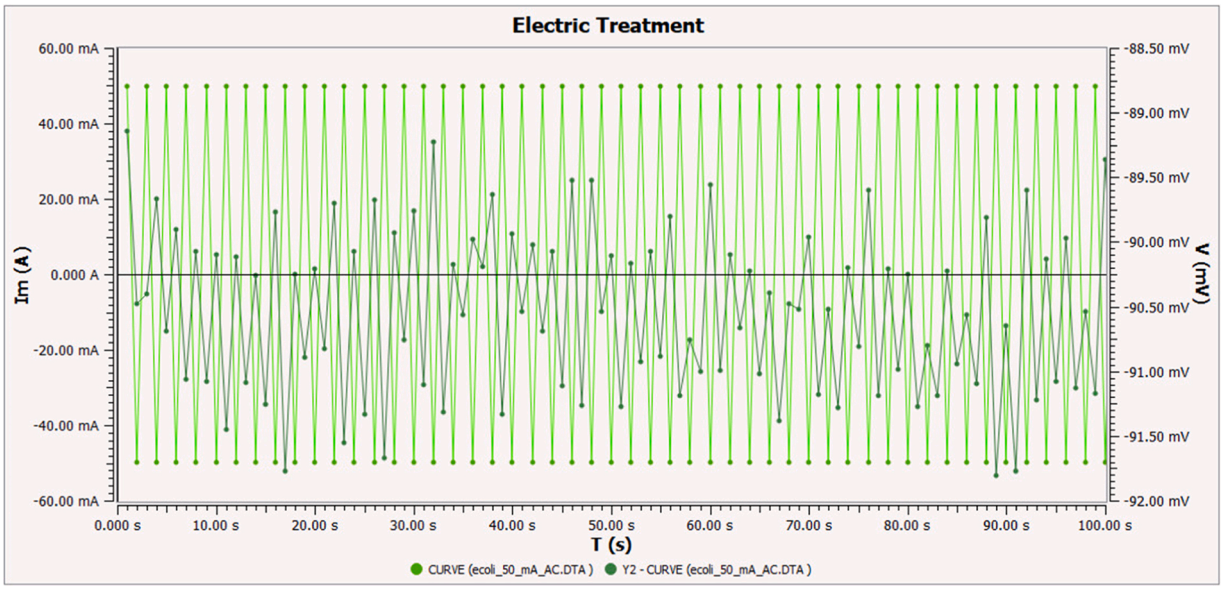



**Fig. 2.** One hundred-second segment of the electrical treatment acquired by the Gamry software: current (A) and potential (mV).

(Eastwell et al., 2006)

In this study, *E. coli* served essentially as a gram-negative model for the study of general bacterial behavior, colonization and potential survival mechanisms on fruit surfaces, since it is recognized as one of the six primary pathogens associated with antimicrobial resistance (Eastwell et al., 2006; Marqués-Marchán et al., 2023). Although *Agrobacterium* targets woody parts of the grapevine and *E. coli* itself is not a pathogen that affects vines or wooden structures, its use provides a basis for understanding bacterial adhesion to plant surfaces, survival dynamics under diverse environmental or postharvest conditions, as well as responses to antimicrobial interventions, which may have broader applications in mitigating bacterial contamination in agricultural environments (Bogino et al., 2013).

Based on the visual analysis of the contamination/degradation state of the grapes (Fig. 3A), it was observed that after 12 days, the contaminated grapes that underwent electrical alternating current stimulation (at day 1) displayed no signs of visual contamination. In contrast, the contaminated grapes without electrical current stimulation showed noticeable deterioration. They appearance were similar to the grapes used as control (washed and microorganisms-free grapes). These preliminarily results suggest that both the washing process and the contamination were carried out efficiently.

*E. coli* contamination in fruit, such as table grapes, does not cause detectable physical changes such as discoloration, abnormal texture or odor that could be associated with spoilage, because *E. coli* typically remains on the surface of the fruit and does not interact directly with the vegetables cells to cause visible damage. However, this pathogen can be transmitted through food when ingested in raw or poorly hygiene

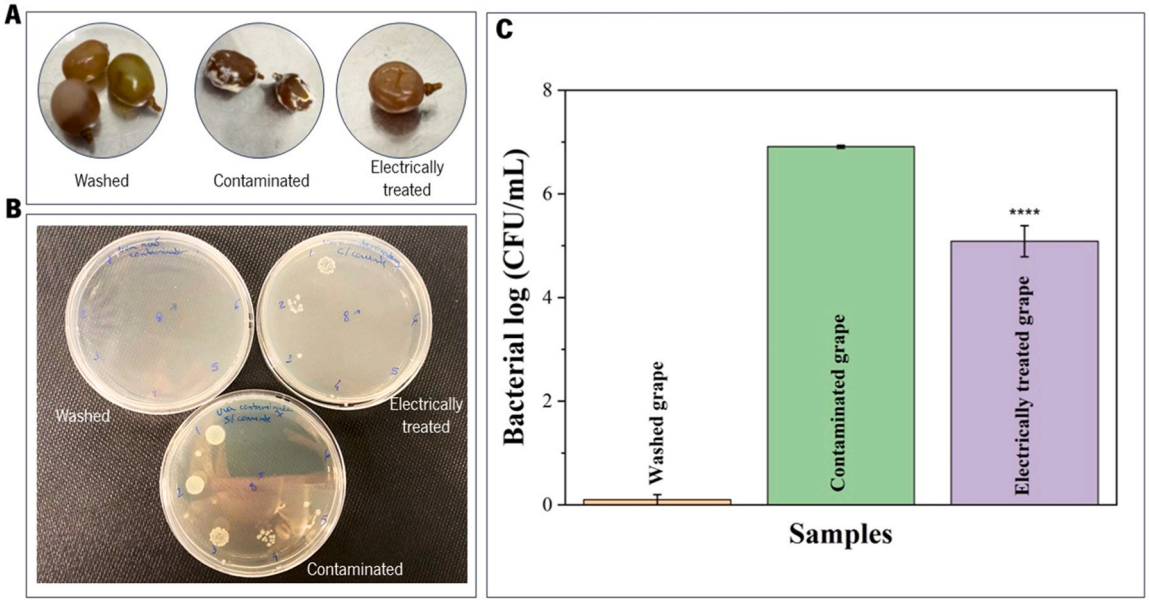



**Fig. 3.** Evaluation of the bactericidal activity of grapes: wash, contaminated by the *E. coli* bacteria without electrical alternating current stimulation and contaminated by the *E. coli* bacteria after applying 50 mA for 10 min, with polarity inversion every 1 s (at day 1): A) Visual appearance 12 days after starting the test; B) Quantitative study based on CFU; C) Bacterial activity as $\log_{10}$ (CFU/mL) of the suspensions obtained after the test with grapes. ****$P < 0.0001$ when compared with lab-contaminated grapes.

products. The risk of transmission increases with inadequate hygiene practices during harvesting, washing or storage (Heaton and Jones, 2008; Luna-Guevara et al., 2019). Although *E. coli* is not directly responsible for causing rot or infections in grapes, it can reach table grapes through several routes, including contamination during cultivation, harvesting, handling and storage. This contamination can come from manure, soil, sewage, surface water or wildlife, but it can also occur during washing, cutting, soaking, packaging and food preparation (Luna-Guevara et al., 2019). Furthermore, its presence, along with the storage conditions encountered in the sterile zipper bags, may have created conditions that favor or accelerate contamination by other microorganisms such as fungi, which present clear visual signs of contamination and are the main causes of grape rot (Di Canito et al., 2021). The most prevalent fungi on table grapes during the postharvest phase are *B. cinerea* and *Penicillium expansum*. *B. cinerea* is a necrotrophic fungus known to cause gray mold disease. *P. expansum* is also a necrotrophic fungus and is widely known for causing blue mould (Chen et al., 2025; He et al., 2019). According to Fig. 3A, these fungi do indeed appear to be present in the contaminated grapes, accelerating their decomposition process. These phytopathogenic fungi are responsible for significant annual economic losses and pose a potential health risk to humans. Therefore, their control is crucial not only during the pre-harvest period but also in postharvest grapes (Di Canito et al., 2021; Pertot et al., 2017).

On the other hand, electrical stimulation was shown not to visually affect the quality and integrity of table grapes. After 12 days, it is natural that the table grapes do not have the fresh appearance they had on day 1, especially since, according to the experimental conditions tested, they remained closed for 12 days in a sterile zipper bag. Still, the stimulated grapes, similar to the control, maintained skin integrity and some firmness, and there did not appear to be significant dehydration, keeping them fresher for longer. Furthermore, even after 12 days under these experimental conditions, the electrically stimulated grapes showed an appearance similar to the control grapes, with no signs of darkening or burning of the grape skin, which would compromise the appearance and acceptance of the product.

The quantitative test confirmed the initial assumption, revealing no microbial growth in the washing control, while only colonies of the *E. coli* strain were detected in the contaminated control (Fig. 3B). A comparison of the contaminated grapes shows that applying 50 mA for just 10 min at day 1, with polarity inversion every 1 s, resulted in a significant reduction of bacterial cells on the grape' surface (electrically treated grapes). For the same dilution, the number of colonies on the test plate agar corresponding to the electrical stimulation was significantly lower than the observed on the agar plate corresponding to the contaminated control (Fig. 3B). Following the electrical stimulus, the reduction was approximately 2 $\log_{10}$ CFU/mL, (Fig. 3C), indicating that approximately 99 % of the *E. coli* previously attached to the berry' surface was eradicated.

SEM was additionally performed to analyze the change in bacterial morphology of electrically treated grapes compared to contaminated grapes and to corroborate previous results.

Through Fig. 4A it is possible to see that the washed grapes used as control showed no signs of contamination in the cellular tissues, indicating that the washing process was effective. Fig. 4B and C shows the predominance of *E. coli* bacteria, for both study conditions, due to the concentration of the inoculum used to contaminate the grape tissues.

In grapes that did not receive electrical stimulation, the bacteria maintained their cellular integrity (Fig. 4B). In contrast, the electrically treated grapes exhibited bacteria destruction and alterations that compromised the structural integrity of bacteria (Fig. 4C). The bacteria showed deep holes/craters in their cell walls, indicative of bacteria lysis, with various fragments and intracellular contents released, which confirmed the deactivation of the bacteria.

In recent years, postharvest decontamination through the application of physical agents, such as ultrasound, in fresh fruits and vegetables has been widely studied for application in the food industry (São José et al., 2014). However, the application of electric current has not been explored in the decontamination of fruits, particularly grapes. Instead, many studies focus on the application of pulsed electric fields as new

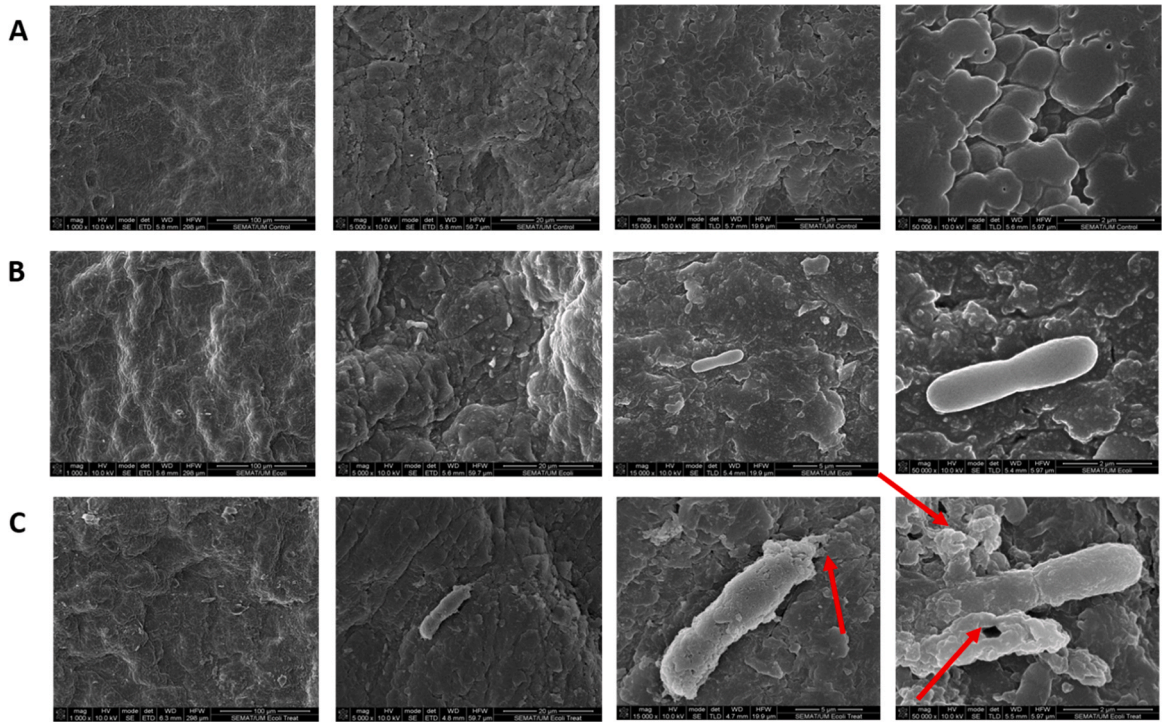



**Fig. 4.** SEM images (1000x, 5000x, 15000x and 50000x magnification) of the grape bark washed (A) contaminated by the E. coli bacteria without electrical current stimulation (B) and contaminated by the E. coli bacteria after applying 50 mA current for 10 min (C). Alteration of the structural integrity of bacteria are highlighted by a red arrow.

methods that can be used to improve product quality in food processing and also to improve yield. For example, many studies focus on the processing of different fruit juices due to the suitability of their physical properties to be processed by electrotechnologies (Evrendilek et al., 2012).

Although the predominant pathogens in EU grapevines are fungi, similar effects are expected in the main fungal pathogens, considering that electric currents can disrupt the cell membrane of both bacterial and fungal cells (Di Canito et al., 2021; Eastwell et al., 2006; Pennington et al., 2018; Pertot et al., 2017). This disruption can lead to leakage of cellular contents, loss of cell integrity, and ultimately, cell death. The lethal effects of electric fields are governed mainly by the intrinsic properties of the microorganism, with the composition of the cell membrane playing a critical role (Hülsheger et al., 1983). For example, the study by Lever et al. (1994) proved that externally applied electric fields in filamentous fungi *Aspergillus nidulans*, *Neurospora crassa* and *Coprinus cinereus* can alter the distribution of certain proteins in the cell membrane, thus inducing polarity and can disturb the transport of calcium ions (Lever et al., 1994). Additionally, the lethal activity of milliampere and microampere current in yeasts has already been confirmed by other studies (Ranalli et al., 2002; Schmidt-Malan et al., 2015). For example, Kalinowski et al. (2004) proved that low-voltage direct current electrostimulation has great clinical potential for the treatment of onychomycosis and perhaps other superficial maladies of fungal etiology (Kalinowski et al., 2004).

The residual microflora may also be eradicated by electrical cues. Nevertheless, this is not necessarily a concern for table grapes. Unlike wine production, where microflora such as yeasts and bacteria play a critical role in fermentation, the presence of microflora is not essential for fresh fruit consumption (Tang et al., 2023). The reduction or elimination of microflora on table grapes can be advantageous, as it directly contributes to inhibiting microbial spoilage and delaying fruit rotting (Torres-Palazzolo et al., 2024). Moreover, by controlling the total microflora, we reduce the risk of secondary infections caused by opportunistic pathogens that might thrive in a compromised microbial community. Nevertheless, it is important to assess the potential risks associated with a sudden regrowth of microflora post-treatment, particularly if any resistant strains survive or if the treatment unintentionally favors certain microbial groups, such as bacteria over yeasts, which could influence spoilage dynamics (Alegbeleye et al., 2022; Torres-Palazzolo et al., 2024).

Future studies should evaluate the long-term effects of low electric current treatment on the survival and regrowth of specific microbial populations, alongside its influence on fruit shelf life and quality. This would help to ensure that the treatment achieves its intended antimicrobial efficacy without unintended consequences, such as promoting microbial resistance or altering the fruit's natural properties.

## 4. Conclusions and future perspectives

This preliminary study aims to demonstrate the concept of using electrical alternating current to prevent grape contamination and avoid health risks. Remarkably, a reduction of up to 99 % in *E. coli* population on the grapes was achieved using electrical currents as low as 50 mA for just 10 min, with polarity inversion every 1 s. Furthermore, this stimulus was sufficient to destroy the cell integrity of the bacteria present on the surface of the grape, causing its deactivation. Although *E. coli* normally remains on the surface of grapes and does not cause visible damage or decay, it poses a high risk as it can be transmitted through contaminated food, especially when hygiene practices during harvesting, washing or postharvest storage are inadequate. Furthermore, this bacterium has been in the health spotlight due to its increased resistance. Based on these results, we anticipate broadening the applicability of the developed methodology to target additional microorganisms, particularly those pathogens commonly affecting grapevines in the EU region. This proposed solution represents an environmentally sustainable approach that mitigates reliance on conventional chemical disinfection agents. It also shows great potential in terms of cost-effectiveness since the intensity of the current used is low and the application time is relatively short. Thus, the operational costs associated with this method are likely to be minimal compared to conventional decontamination approaches. However, while this method is promising as a proof of concept, scaling it up for industrial application will require the development of specialized devices. These devices must ensure uniform treatment of entire grape bunches, guaranteeing consistent application and maintaining efficacy through a polymeric conductive net. Further research will focus on the validation of this protocol against other pathogenic identified microorganisms of interest.

## Author contributions

Conceptualization, M.P.F., F.S. and M.F.F.; methodology, M.P.F., F. R. and M.F.F; writing—first draft, M.P.F and F.R; writing—review and editing, V.F.C. and M.F.F; su-pervision, V.F.C., M.F.F and F.S.; funding acquisition, F.S. and M.F.F. All authors have read and agreed to the published version of the manuscript.

## CRediT authorship contribution statement

**Fernandes Margarida M.:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Rodrigues Flávio:** Methodology, Investigation. **Fernandes Mariana P.:** Writing – original draft, Methodology, Investigation. **Silva Filipe S.:** Supervision, Conceptualization. **Cardoso Vanessa F.:** Writing – review & editing, Investigation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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